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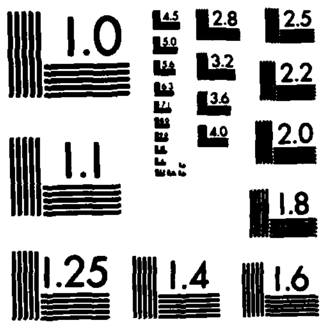
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REGIONAL PETROLEUM RESERVE
EAST COAST

VOLUME III

POTENTIAL STORAGE SITES
RELATED ENGINEERING
STUDIES

AD-A144 651

DEPARTMENT OF ENERGY
UNITED STATES OF AMERICA

U.S. ARMY
CORPS OF ENGINEERS
HUNTSVILLE DIVISION

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VOLUME I PRESENTS A DETAILED DESCRIPTION OF THE PROCEDURES AND RESULTS OF A SITE IDENTIFICATION AND EVALUATION PROCESS UNDERTAKEN IN SUPPORT OF THE REGIONAL AND NONCONTIGUOUS PETROLEUM RESERVE (RPR) PROPOSAL. THE CRITICAL FACTORS AND RATING GUIDANCE USED FOR INITIAL SCREENING ARE DESCRIBED IN APPENDIX B. POTENTIAL SITES, ACCEPTED DURING THE INITIAL SCREENING, WERE SUBJECTED TO A FINAL SCREENING WHERE THEY WERE POINT-SCORED ON THE BASIS OF AN EVALUATION OF SPECIFIC CHARACTERISTICS. THE SCORING SYSTEM, AS ESTABLISHED

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BY THE REVIEW AND SUMMATION TEAM, IS DESCRIBED IN APPENDIX C. SITE SCORES AND RANKING UNDER EACH OF THE THREE STORAGE MEDIA ARE SHOWN IN APPENDIX D.

VOLUME II PROVIDES CONCEPTUAL DESIGN DRAWINGS, CONSTRUCTION COST ESTIMATES, AND A LIFE CYCLE COST ECONOMIC ANALYSIS CONDUCTED TO IDENTIFY, AND QUANTIFY, UNIQUE ECONOMIC ADVANTAGES THAT MAY BE ATTRIBUTABLE TO THE CANDIDATE SITES.

VOLUME III PROVIDES THREE RELATED ENGINEERING STUDIES: (1) DEVELOPMENT OF CONDUCTIVE AND CONVECTIVE HEAT TRANSFER CONCEPTS FOR NO. 6 RESIDUAL OIL. (2) FEASIBILITY OF HEATING RESIDUAL OIL STORAGE FACILITIES WITH SOLAR ENERGY. (3) AN ANALYSIS ON LEASE VS PURCHASE OF STORAGE FACILITIES.

EAST COAST

REGIONAL PETROLEUM RESERVE
(RPR)

VOLUME III

POTENTIAL STORAGE SITES
RELATED ENGINEERING STUDIES

Prepared by

US Army Corps of Engineer
Huntsville Division

30 September 1980

FOREWORD

Identification and evaluation of potential storage sites for the Regional Petroleum Reserve were completed and submitted to DOE in May 1980 as Volume I of a 3-volume set. In support of Volume I, concept designs, construction cost estimates, and life cycle costs have been prepared and comprise Volume II. Volume III contains three related engineering studies:

(1) Development of conductive and convective heat transfer concepts for No. 6 residual oil

(2) Feasibility of heating residual oil storage facilities with solar energy

(3) An analysis on lease vs purchase of storage facilities

The related studies appear in this volume as Appendix A, B, and C.

APPENDIX A

HNDTR-80-45-SP

EAST COAST

REGIONAL PETROLEUM RESERVE
(RPR)

NO. 6 OIL HEATING CONCEPT STUDY

Prepared by

U.S. ARMY CORPS OF ENGINEERS
HUNTSVILLE DIVISION

30 September 1980

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SUMMARY

The design concept of a heating system for a No. 6 residual fuel oil storage tank has been investigated. In this study, all the thermodynamic and heat transfer properties representative of No. 6 oil were collected. Numerical simulation models for both convective and conductive heat transfer concepts were developed, without consideration of the phase change, and convective/conductive concepts were tested by using the appropriate thermodynamic properties of No. 6 oil. In this preliminary study, we concluded that th[illegible]t condition for No. 6 o[illegible] withdrawal is to keep the oil in a liquid state. Pure conduction [illegible]l not be efficient enough to heat up the oil to the desired conditi[illegible] for withdrawal. The convective motion (thermal syphone effect) can be developed and may lead to the desired conditions for proper withdrawal; however, more numerical tests that take into account the phase change are needed for further clarification of the convection concept.

SECTION 1

INTRODUCTION

Residual Fuel Oil or No. 6 is a petroleum-fuel product usually collected at the bottom of fractionating columns. Residual oil is used widely to generate steam for industrial process use, generation of electrical power, and for high temperature furnaces required for kilns, dryers, etc.

Under the proposed Department of Energy Regional Petroleum Reserve Program (RPR), 20 million barrels of No. 6 fuel oil are to be stored in DOE-designated Regions 1, 2, 3, and 4. Of this total at least 10 million barrels will be stored in northeastern states which comprise DOE Regions 1 and 2. Based on program criteria, four complete withdrawals and refills are anticipated over a 20-year lifetime with the entire storage system in lay-away or in a dormant state between drawdowns.

The purpose of this study is to investigate the thermodynamic and heat transfer properties of No. 6 residual oil in the dormant or lay-away state and provide a design concept for a heating system to prepare the stored oil product for drawdown. To accomplish this, it was assumed that No. 6 fuel oil will be stored in uninsulated steel tanks having a capacity of 1.42 million barrels each.

Section 2 of this study analyzes the physical properties of No. 6 in both the liquid and solid states. Numerical simulation models in two dimensions are described in detail. Section 3 presents useful relationships for estimating the thermodynamic properties, and Section 4 gives the conclusions and recommendations derived from this investigation.

SECTION 2

PHYSICAL PROPERTIES OF NO. 6 OIL

No. 6 fuel is a complex, inhomogenous mixture of hundreds, perhaps thousands, of compounds in multiple phases (liquid and solid states). In general, No. 6 fuel oil will consist of colloids, such as asphalt, solids, and wax crystals, disseminated in a liquid matrix. When No. 6 fuel oil is cooled, its viscosity increases, through a combination of processes, which exhibit a highly non-linear dependence on temperature. At 0°C (32°F), certain compounds in the No. 6 fuel oil remain in a liquid state while the remaining compounds solidify. To a large extent, heating will liquify the solid compounds to a liquid state. At 150°C (302°F) a number of the compounds will undergo pyrolysis from prolonged heating.

No. 6 fuel oil has a pour point temperature of 10°C to 16°C (50° to 61°F).[1] Between 8° and 13°C (46°F-55°F) was crystals appear in the oils, and No. 6 becomes thixotropic. In this state, wax contents in oil become a solid matrix and lighter oils exist as liquid inside the wax matrix. In this state viscosity increases to the point that the fluid cannot be moved without mechanical agitation.

Table I shows commercial hydrocarbon fuel types and their applications. No. 6 fuel oils usually have relative density (R.D.) greater than 0.90. Because of the peculiarity of the No. 6 oil, its physical properties are difficult to find. Therefore, data was collected on substances with properties as close as possible to No. 6 oil; then, the data was extrapolated.

TABLE I. COMMERCIAL HYDROCARBON FUEL TYPES AND APPLICATIONS (ref. 2)

Fuel type		Specification* reference	Typical R.D.	Applications
liquefied gases	L.N.G.		0.43	lighting, space heating, hot-water supply, cooking
	L.P.G.	BS 4250	0.52	drying, power production, metallurgical processes, chemical feedstock, hot-air ballooning
gasolines	Avgas	D.Eng.R.D.2485	0.70/ 0.72	aero s.i. piston engines
	Mogas	BS 4040	0.73	road vehicle s.i. piston engines, and portable lightweight units, e.g. tree saws
	Avtag	D.Eng.R.D.2486	0.77	Aero gas-turbine engines (military)
kerosines		BS 2869 C1	0.80	free-standing flueless domestic heaters (aromatics removed)
		BS 2869 C2	0.80	heaters with flues (aromatics removed)
	T.V.O.		0.80	agricultural tractors (aromatics added; vaporising heat)
	Avtur	D.Eng.R.D.2494	0.80	aero gas-turbine engines *(civil)*
	Avcat	D.Eng.R.D.2498	0.82	aero gas-turbine engines (naval)
gas oils	Derv	BS 2869 A1	0.84	high-speed automobile c.i. piston engines
		BS 2869 A2	0.84	general-purpose c.i. piston engines
		BS 2869 D	0.85	central-heating installations, drying
diesel fuels and heating oils		BS 2869 B1	0.87	low-speed marine and power-generating c.i. piston engines (ambient storage)
		BS 2869 B2	0.90	heavier versions of above (ambient storage)
		BS 2869 E	0.90	industrial heating and drying (heated storage)
fuel oils		BS 2869 F	0.95	some heavy c.i. piston engines (heated storage)
		BS 2869 G	0.95	under-boiler combustion industrial heating and drying (heated storage)
		BS 2869 H	0.95	special purposes (heated storage)

BS = British Standard

*Fuel specification symbols appeared in some of the following figures.

Data collected are (i) density, (ii) specific heat, (iii) viscosity, (iv) thermal conductivity, (v) vapor pressure, (vi) internal energy, (vii) heat of fusion, and (viii) other thermodynamic properties.

2.1 RELATIVE DENSITY

The density of a liquid sample is defined as the mass of the sample occupying the unit volume at the stated temperature of 15°C (59°F). The density of a liquid sample relative to that of pure water is derived as follows:

$$\text{relative density at } T_1/T_2 = \frac{\text{mass of given vol. of sample at } T_1}{\text{mass of equal vol. of distilled water at } T_2}$$

$$= \frac{\text{density of sample at } T_1}{\text{density of distilled water at } T_2}$$

One value of the standard reference temperature T_2 is 15.5°C (59.5°F). At a reference temperature of 4°C (39.2°F) the density of water is unity, hence density and relative density of a sample then becomes numerically equal.

The relative density of the petroleum product as a function of temperature is shown in Figure 1.

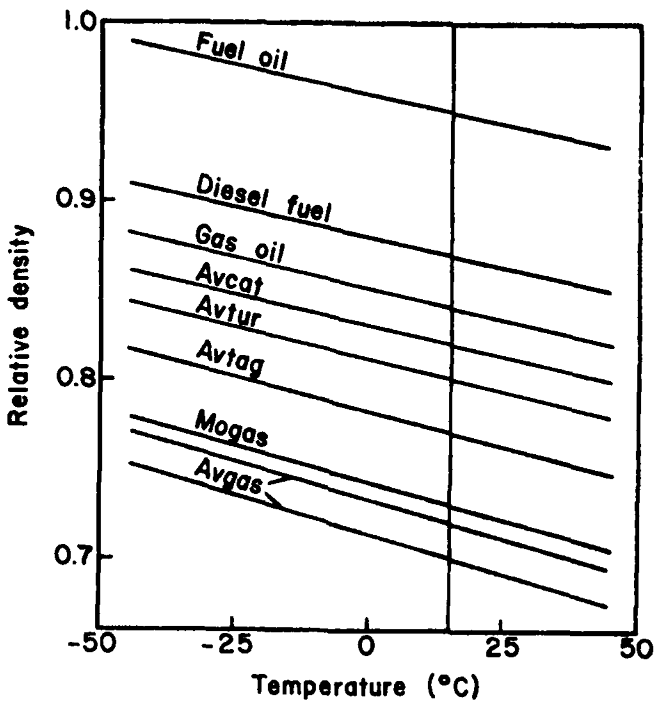


Figure 1. Variations in relative density with temperature for representative commercial hydrocarbon fuels. (ref 2)

The American Petroleum Institute (API) defines the density of petroleum products by API degree. The relationship between relative density and API degree is given by

$$\text{degree API} = \frac{141.5}{\text{relative density at } 60/60°\text{F}} - 131.5$$

Figure 1 shows that density varies almost linearly over a wide range of temperatures. Below 15°C (59°F), No. 6 fuel oil becomes thixotropic and cannot be poured freely without mechanical agitation.

2.2 SPECIFIC HEAT

The specific heat as a function of API (American Petroleum Institute) gravity and temperature is given in Figure 2.

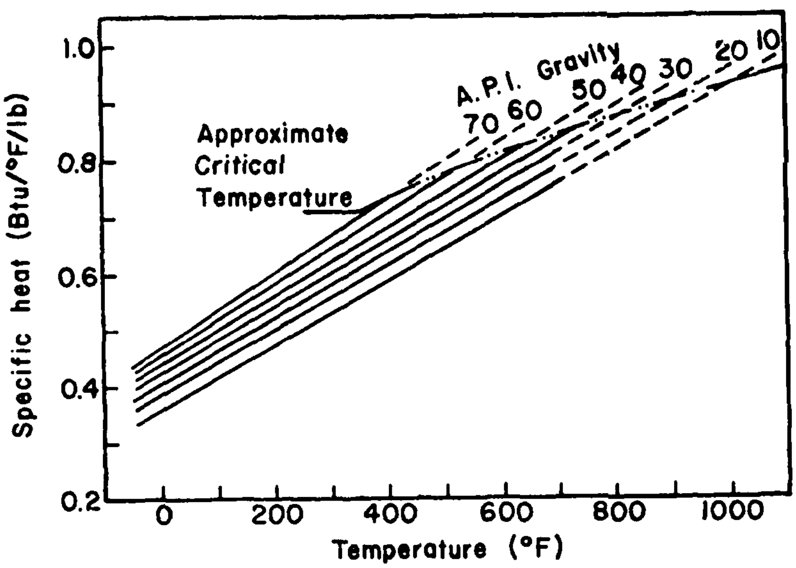


Figure 2. Specific heat of hydrocarbon products vs temperature. (ref 3)

2.3 VISCOSITY

The weak van der Waals-type forces between molecules provide cohesion to a body of liquid, and hence a resistance to internal displacement and flow. This resistance is termed the viscosity. Since liquid fuels expand with temperature rise, intermolecular distances increase and the viscosity falls.

The dynamic viscosity (η) of a sample may be defined as the shearing force on the unit area of either of two parallel planes at unit distance apart when the space between planes is filled with the sample fuel, and one of the planes moves with unit velocity in its own plane relative to the other. Hence, the force per unit area produces a unit velocity gradient, such that the dynamic viscosity can be obtained. Kinematic viscosity (ν) is used for most calculations. The kinematic viscosity is defined as the quotient of the dynamic viscosity and the density of the sample. Hence $\nu = \eta/\rho$, where ρ = the density of the sample. With the metric system, the unit of kinematic viscosity is the cm^2/s, or Strokes (St.). Here again, the smaller unit is more convenient, that is, 1 cSt. = 0.01 St. = 1 mm^2/s. Kinematic viscosity is of general interest in fuel technology in connection with the pumping and atomization of liquid fuels.

For petroleum-type fuels, the variation of kinematic viscosity with temperature can be expressed by

$$10g\ (\nu + a) = n \log T + b,$$

where a, n and b are constants. These constants have been adopted and graphical charts standarized by ASTM and "Refutas" methods. The linear variation of kinematic viscosity with temperature is shown in Figure 3.

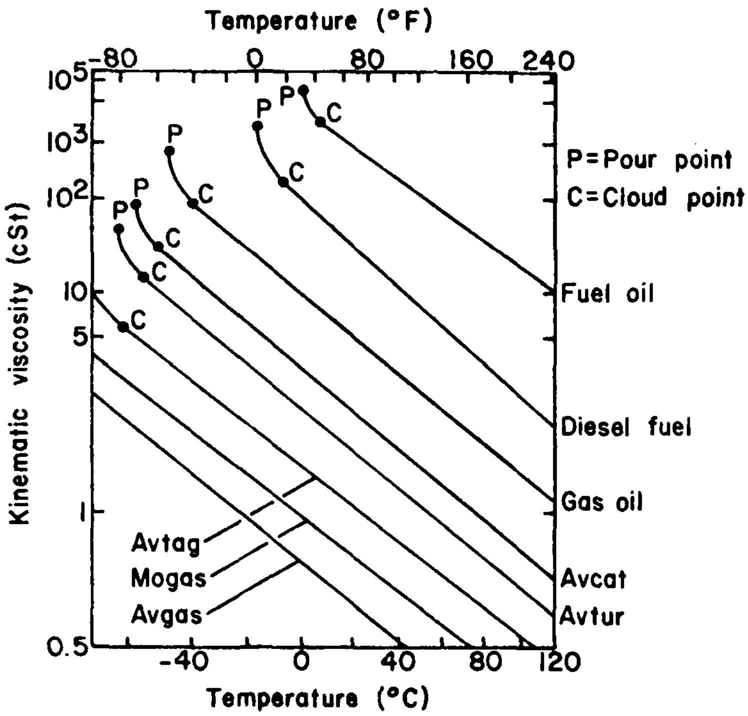


Figure 3. Viscosity-temperature curves for representative commercial hydrocarbon fuels. (ref 2)

Viscosity varies almost linearly until the temperature falls below the cloud point denoted by C in Figure 3. The cloud point is the temperature where haziness appears in the oil due to the formation of

wax crystals. Pour point is the temperature below which oil ceases to move without mechanical agitation. Between pour point and cloud point, fuels behave as thixotropic materials since, despite their apparent solidification, some of the lighter fraction still exists as liquid droplets within the porous wax matrix and agitation serves to break down the wax matrix to restore some fluidity to the liquid-wax slurry. Fuel oil viscosity is very critical in relation to pumping through a fuel system and atomization at the furnace. Since viscosity increases rapidly as temperature falls, internal or external heaters are usually required for storage of heavy oils.

2.4 THERMAL CONDUCTIVITY

The thermal conductivity of petroleum products and water as functions of temperature is shown in Table II. Thermal conductivity of fuel oil is generally one order of magnitude less than that of water. Therefore, conduction effects of heat transfer in oil are almost negligible. Thermal conductivity does not change drastically over a wide range of temperature. Assuming No. 6 fuel oil is a homogenous liquid mixture, an interpolation of the data can be made to estimate the No. 6 fuel thermal conductivity.

2.5 VAPOR PRESSURE

The absolute vapor pressure of a liquid fuel may be defined as the pressure exerted by the vapor above the free surface of the liquid at the given temperature. Vapor pressure gives a significant indication of the extent of vapor loss likely during fuel storage in

TABLE II. THERMAL CONDUCTIVITY OF PETROLEUM PRODUCTS (Btu/hr ft °F) (ref. 3)

Temperature, °F	A.P.I. at 60°F	Water	10	20	30	40	50	60	Asphalt	Wax
	Sp. Gr. 60/60		1.0	0.9341	0.8762	0.8521	0.7796	0.7389		
0		0.322*	0.0683	0.0735	0.0783	0.0833	0.0875	0.0925	0.1	0.133
200		0.410	0.0642	0.0691	0.0735	0.0783	0.0825	0.0875	(Average from	
400		.....	0.0600	0.0642	0.0691	0.0735	0.0775	0.0815	32°F to	
600		.....	0.0558	0.0600	0.0642	0.0683	......	......	melting-	
800		.....	0.0525	0.0558	0.0591	......	......	......	point)	

*At 35°F, also 0.357 at 100°F.

the vented tank, and the tendency for vapor release and possible vapor lock in pipelines during transfer. A typical variation of vapor pressure is shown in Figures 4 and 5, as a function of relative density or temperature.

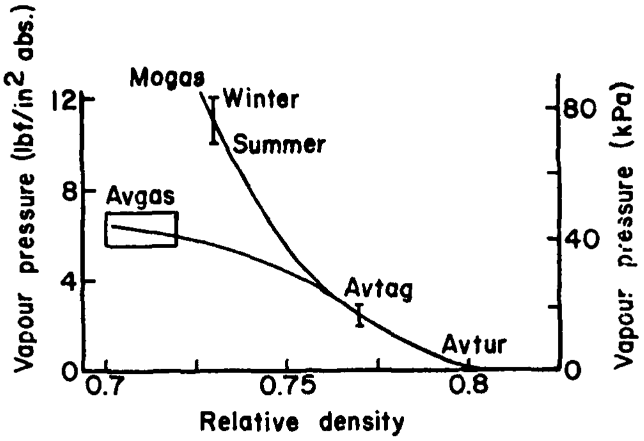


Figure 4. Variation of vapor pressure with relative density for representative commercial hydrocarbon fuels.

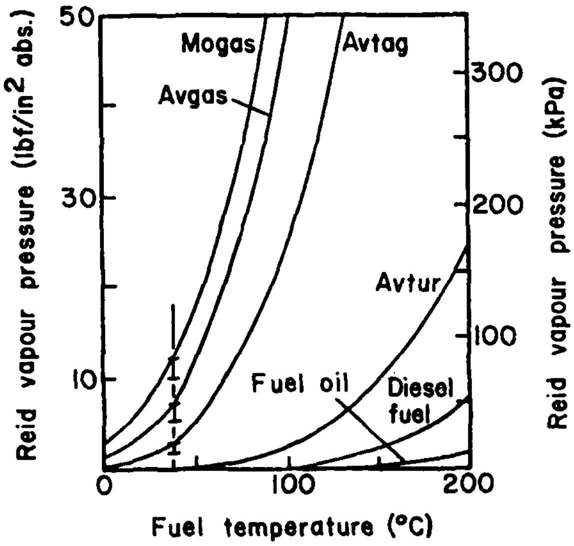


Figure 5. Variation of vapor pressure with temperature for representative commercial hydrocarbon fuels.

Reid vapor pressure is defined as the equilibrium gauge pressure exerted by petroleum vapor in a sealed bomb which is placed in a water bath controlled thermostatically to 37.8°C (100°F). For fuel oil, the vapor pressure is actually very low for temperatures less than 200°C (392°F) as seen in Figure 5.

2.6 INTERNAL ENERGY

The internal energy for petroleum products is given in Table III.

TABLE III. INTERNAL ENERGY (H; Btu/lb mass)
OF PETROLEUM PRODUCTS (ref. 4)

Temp. °F	10 API	20 API
-20	59	62
0	64	67
20	74	78
40	82	86
60	90.5	96
80	98.5	104

The base value of internal energy is 0 btu/lb mass at -128°C (-200°F). Figure 6 shows a graphical representation of the internal energy of oil as a function of its temperature. Above -6.7°C (20°F), internal energy behaves linearly as a function of temperature. As previously

noted, No. 6 fuel oil is a complex mixture of multiphases and of many compounds. Therefore, the internal energy in the temperature range of 0^{o}-20^{o}C (32^{o}-68^{o}F) can only be approximated and is shown as a gap on the chart.

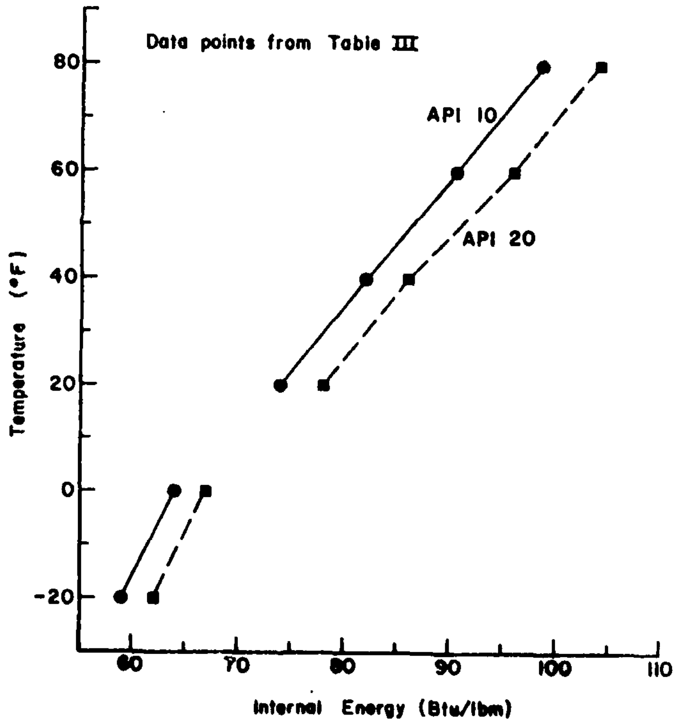


Figure 6. Internal energy of hydrocarbon fuels.

2.7 HEAT OF FUSION

As previously discussed, the stored cool No. 6 fuel oil has the characteristics of a thixotropic material due to its crystallized wax components along with its liquid components. The heat

TABLE IV. HEAT OF VAPORIZATION (ref. 3)

Temp., °F	Latent heat, Btu per lb. for the following API gravities				
	60	50	40	30	20
200	138.2	136.9			
300	123.3	123.3	123.4		
400	107.7	109.0	110.5	111.8	
500	.....	93.8	96.7	99.3	103.0
600	.....	.....	82.0	86.1	91.3
700	.....	.....	.....	73.8	78.5
800	.....	.....	.....	.....	64.7

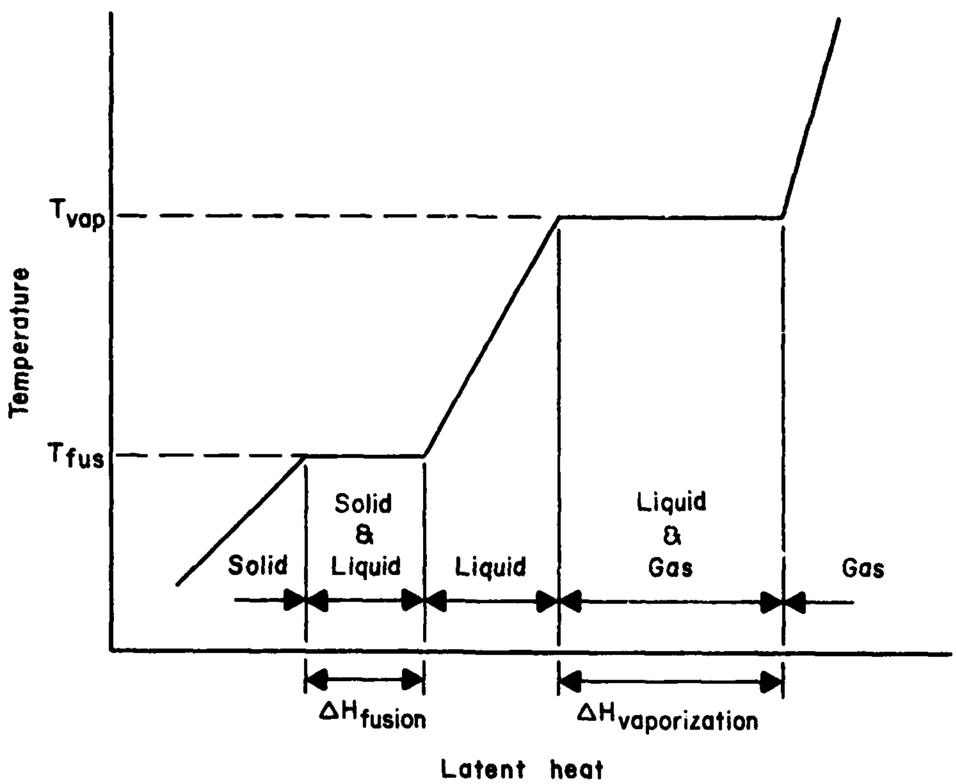


Figure 7. Schematic phase diagram of petroleum product.

of fusion of these wax components must be estimated and utilized in any No. 6 fuel oil heat transfer study.

Assuming that No. 6 fuel oil can be represented by a homogenous mixture of API 10-20 oil and paraffin wax, a linear interpolation between API-10 and paraffin wax, provides an estimate of its heat of fusion. Table V presents such an interpolation in which the API-10 oil heat of fusion was estimated from Figure 6 and the paraffin wax data from Table VI.

TABLE V

	API 10	No. 6 Oil	Paraffin Wax
T_{Fusion}	15°F	60°F	122°F
ΔH_{Fusion}	10 Btu/lb mass	27.6 Btu/lb mass	63.8 Btu/lb mass

In the "Storage Tank Guide,"[5] furnished by DOE, the following relation is used to estimate No. 6 fuel oil heat of fusion

$$(\Delta H)_{Fusion} \equiv Cp\ (T_f - T_p)$$

Cp is the specific heat and T_f and T_p indicate the temperature at flash and pumping points respectively. Using the data provided in the same reference, the No. 6 fuel oil heat of (Ref 5) fusion may be estimated as follows:

TABLE VI. MELTING POINT AND HEAT OF FUSION OF VARIOUS SUBSTANCES (ref 6)

Name	°C		°F	Heat of Fusion	
				Calories per Gram	B per
Beeswax................	62	=	143.6	42.3	76.1
Benzol.................	2	=	35.6	29.1	52.4
Carbon dioxide.........	-56.3	=	133.4	43.8	78.8
Cresol.................	34	=	93.2	26.3	47.3
Glycerin...............	13	=	55.4	42.5	76.5
Naphthalene............	79.2	=	175.0	35.5	63.9
Nitrobenzol............	-9.2	=	15.4	22.3	40.1
Paraffin...............	50.0	=	122.0	35.1	63.8
Phenol.................	25.4	=	77.9	24.9	44.8
Phosphorus.............	27.4	=	81.4	4.74	8.5
Silica.................	1750.0	=	3183.0	258.0	464.5
Sulphur................	115.0	=	239.0	9.37	16.9

$$(\Delta H)_{Fusion} \quad 0.44\ (185-120)$$

$$= 28.6\ \text{Btu/lb mass}$$

Good agreement was obtained between the two methods of estimating No. 6 fuel oil heat of fusion. This may imply that simple linear interpolation theory can be used as a lowest order appro imation.

study of the thermodynamic properties are needed.

2.8 USEFUL RELATIONS FOR ESTIMATING THERMODYNAMIC PROPERTIES

Assuming an equilibruim condition between the liquid and solid states of a pure substance, the following relations may be written,

$$g_f = g_s$$

$$g_f = g_g$$

where "g" is the Gibbs function per unit mass, subscript f and s represent liquid and solid state respectively.

$$g = h - TS,$$

where h is enthalpy, T, temperature and S is the entropy per unit mass.

$$g_s = h_s - T_s S_s = g_f = h_f - T_f S_f,$$

during the phase change. $T_s = T_f$,

$$\Delta h_{sf} = h_s - h_f = T_s \Delta S_{sf} = T_s (S_s - S_f)$$
$$= Q,$$

with Q being the heat flow during the phase transition.

An empirical approach is used to estimate the transport properties of viscosity and heat transfer coefficient. No. 6 fuel oil is assumed to be a homogenous mixture of paraffin and other oil products in which ν^L_{wax}, ν^S_{wax}, k^L_{wax} and k^S_{wax} are the viscosity and heat transfer coefficient in the liquid and solid states respectively.

$$\nu^L_{06} = f_1(P,T)\, \nu^L_{wax}$$
$$k^S_{06} = f_2(P,T)\, k^S_{wax}$$

Functions f_1 and f_2 are arbitrary functions of pressure and temperature which relate No. 6 fuel oil properties to those of the paraffin wax. For the lowest order of approximation, they are represented by constants.

To find a realistic functions of f_1 and f_2, the kinetic theory for liquids and solids and statistical thermodynamics together with correlation studies with experimental data should be used. Such an effort is beyond the scope of this study. Therefore, f_1 and f_2 are considered to be constants for this investigation.

SECTION 3

SIMULATION MODEL

3.1 THEORY

The density of No. 6 oil changes very little over the temperature range of 10°C to 50°C (50°F to 122°F) allowing the use of incompressible fluid equations for this investigation. A rectangular tank is used for numerical analysis purposes by employing Cartesian coordinates. The rectangular tank is shown in Figure 8 with the coordinate system employed. It is further assumed that the thermodynamic properties are constant over the range of temperature variations.

Under these assumptions, the equations of motion are

Continuity equation

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{3.1}$$

x-Momentum equation

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho_o}\frac{\partial p}{\partial x} + \nu_o\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \tag{3.2}$$

y-Momentum equation

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho_o}\frac{\partial p}{\partial y} - g\beta(T - T_o) + \nu_o\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) \tag{3.3}$$

Energy equation

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{\lambda}{\rho_o C_p}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) + \frac{\dot{Q}(x,y)}{\rho_o C_p} \tag{3.4}$$

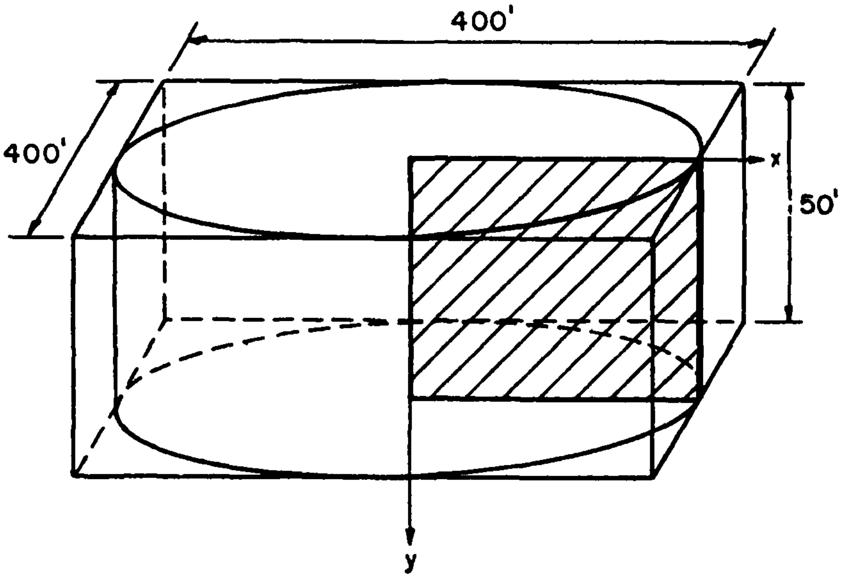


Figure 8. Storage tank dimension and coordinate system.

In Equations (3.1)-(3.4), ρ_o = density, u = velocity in x-direction, v = velocity in y-direction, p = pressure, ν = kinematic viscosity, g = gravitational acceleration, β = thermal expansion coefficient, T = temperature, λ = thermal conductivity, C_p = specific heat and Q denotes internal energy generation rate. As internal energy changes occur, it should be noted that gravitational effects come in only as a buoyancy force in accordance with the Boussinesq approximation. This approximation is valid as long as temperature increment $(T-T_o)$ is small in comparison with $1/\beta$; it is the essential factor for the phenomena of natural convection heat transfer.

Define the dimensionless variables:

$$X = \frac{x}{H_y}, \quad Y = \frac{y}{H_y}, \quad \tau = \frac{t}{H_y^2/\nu_o}, \quad U = \frac{uH_y}{\nu_o}, \quad V = \frac{vH_y}{\nu_o}$$

$$\psi = \frac{\psi}{\nu_o}, \quad \Omega = \frac{\omega}{H_y^2\nu_o}, \quad \theta = \frac{T - T_o}{T_1 - T_o}, \quad Q = \frac{\dot{Q}}{\lambda(T_1 - T_o)/H_y^2} \tag{3.5}$$

where H_y denotes height of the tank and T_1 denotes reference temperature imposed at the bottom of the tank, which can be ground temperature. Introducing the stream function into equation (3.1), eliminating pressure terms from the momentum equation, and introducing the dimensionless variables defined in equation (3.5), the equation of motion can be written in non-dimensional form as follows:

$$\Omega = - \left(\frac{\partial^2}{\partial X^2} + \frac{\partial^2}{\partial Y^2}\right) \psi \tag{3.6}$$

$$\frac{\partial \Omega}{\partial \tau} + \frac{\partial (U\Omega)}{\partial X} + \frac{\partial (V\Omega)}{\partial Y} = - G_r \frac{\partial \theta}{\partial X} + \left(\frac{\partial^2}{\partial X^2} + \frac{\partial^2}{\partial Y^2}\right) \Omega \tag{3.7}$$

$$\frac{\partial \theta}{\partial \tau} + \frac{\partial (U\theta)}{\partial X} + \frac{\partial (V\theta)}{\partial Y} = \frac{1}{P_r} \left(\frac{\partial^2}{\partial X^2} + \frac{\partial^2}{\partial Y^2}\right) \theta + \frac{1}{P_r} Q \tag{3.8}$$

$$U = \frac{\partial\psi}{\partial Y}, \quad V = -\frac{\partial\psi}{\partial X}, \tag{3.9}$$

where ψ denotes stream function, Ω vorticity, G_r = Grashof number and P_r = Prandtle number. The dimensionless form of the equations has an advantage over the dimensional form when interpreting the results of the analysis for various cases.

Figure 9 shows the domain of analysis with initial and boundary conditions for each dependent variable in dimensional and in non-dimensional form. The dependent variables (ψ, Ω, θ) are computed from equations (3.6), (3.7) and (3.8). Equation (3.9) provides the relationship between vorticity and the stream function. The independent variables are time (t) and the spatial coordinates (x, y).

3.2 NUMERICAL METHOD

The Crank-Nicholson type Alternating Direction Implicit (C-NADI) numerical method is applied for the solution of equations (3.7) and (3.8). A successive over-relaxation technique is used for equation (3.6). Figure 10 shows the flow diagram.

The Crank-Nicholson type ADI scheme used for the energy equation consecutively, over two half-time steps, each of a duration of $\Delta\tau/2$, is

$$\frac{\theta^*_{i,j} - \theta^n_{i,j}}{\Delta\tau/2} + \frac{(U\theta)^*_{i+1,j} - (U\theta)^n_{i=1,j}}{2\Delta X} + \frac{(V\theta)^n_{i,j+1} - (V\theta)^n_{i,j-1}}{2\Delta Y}$$

$$= \frac{1}{P_r}\left[\frac{\theta^*_{i+1,j} + \theta^*_{i-1,j} - 2\theta^*_{i,j}}{(\Delta X)^2} + \frac{\theta^n_{i+1,j} + \theta^n_{i-1,j} - 2\theta^n_{i,j}}{(\Delta Y)^2}\right]$$

$$+ \frac{1}{P_r} Q^n_{i,j} \tag{3.10}$$

followed by

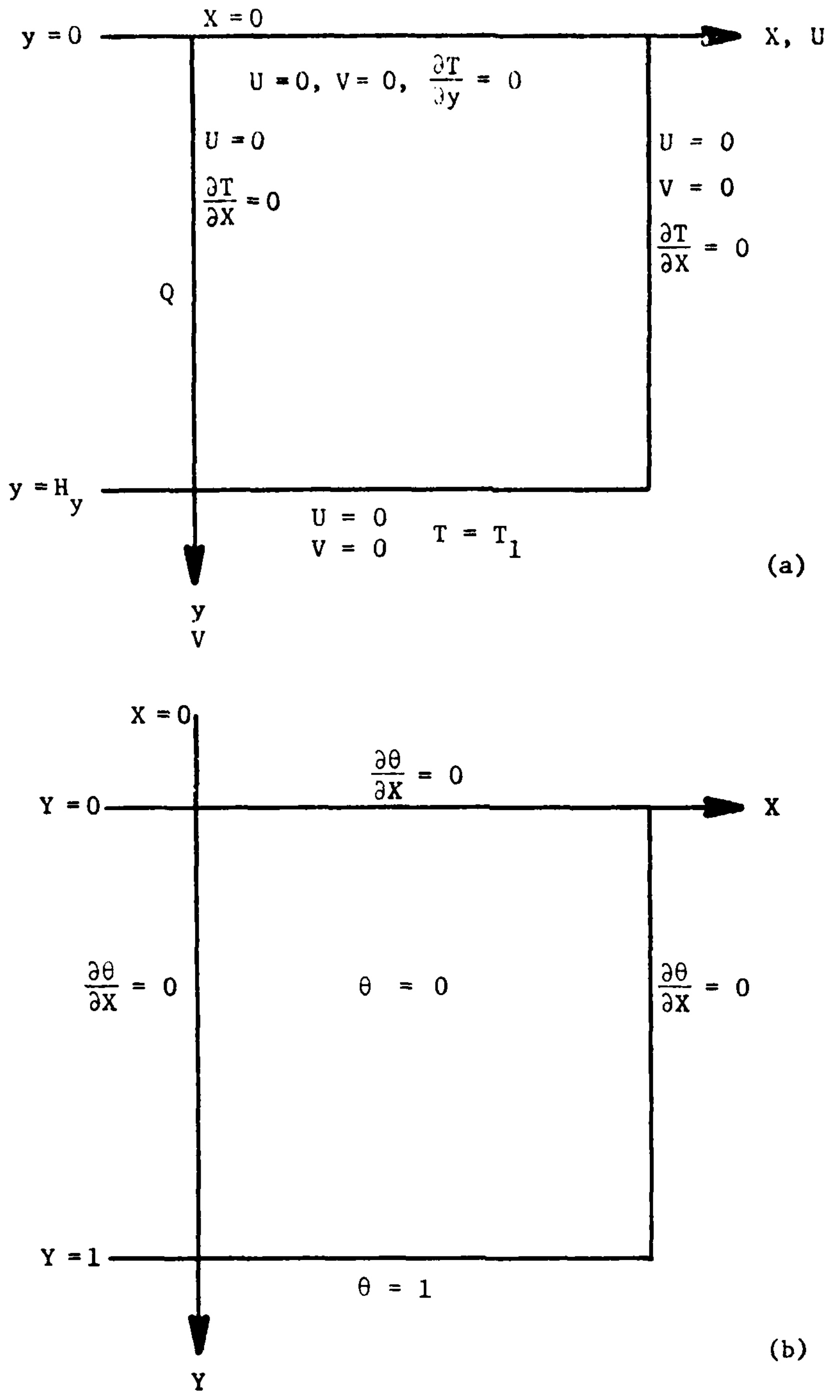


Figure 9. Computational domain with initial and boundary conditions in (a) dimensional form; (b) non-dimensional form.

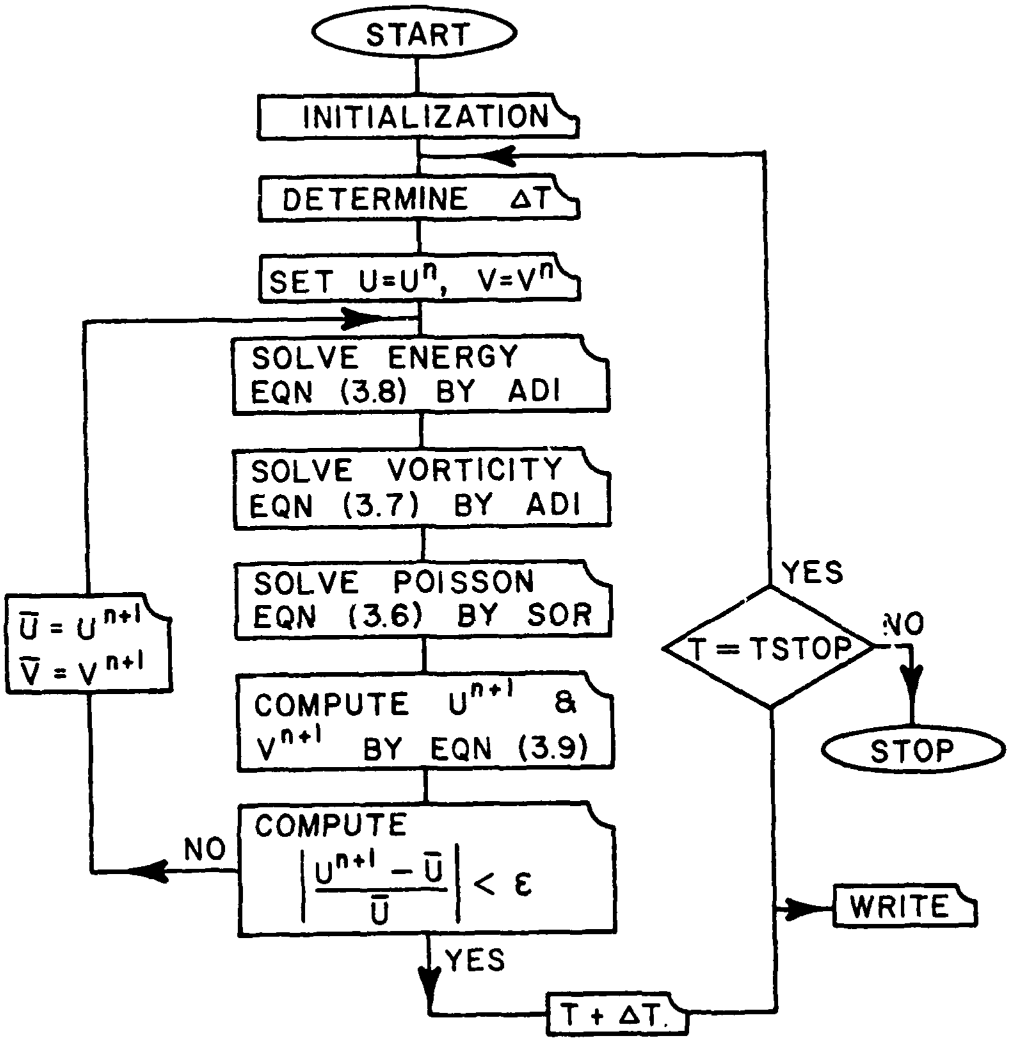


Fig. 10. FLOW DIAGRAM

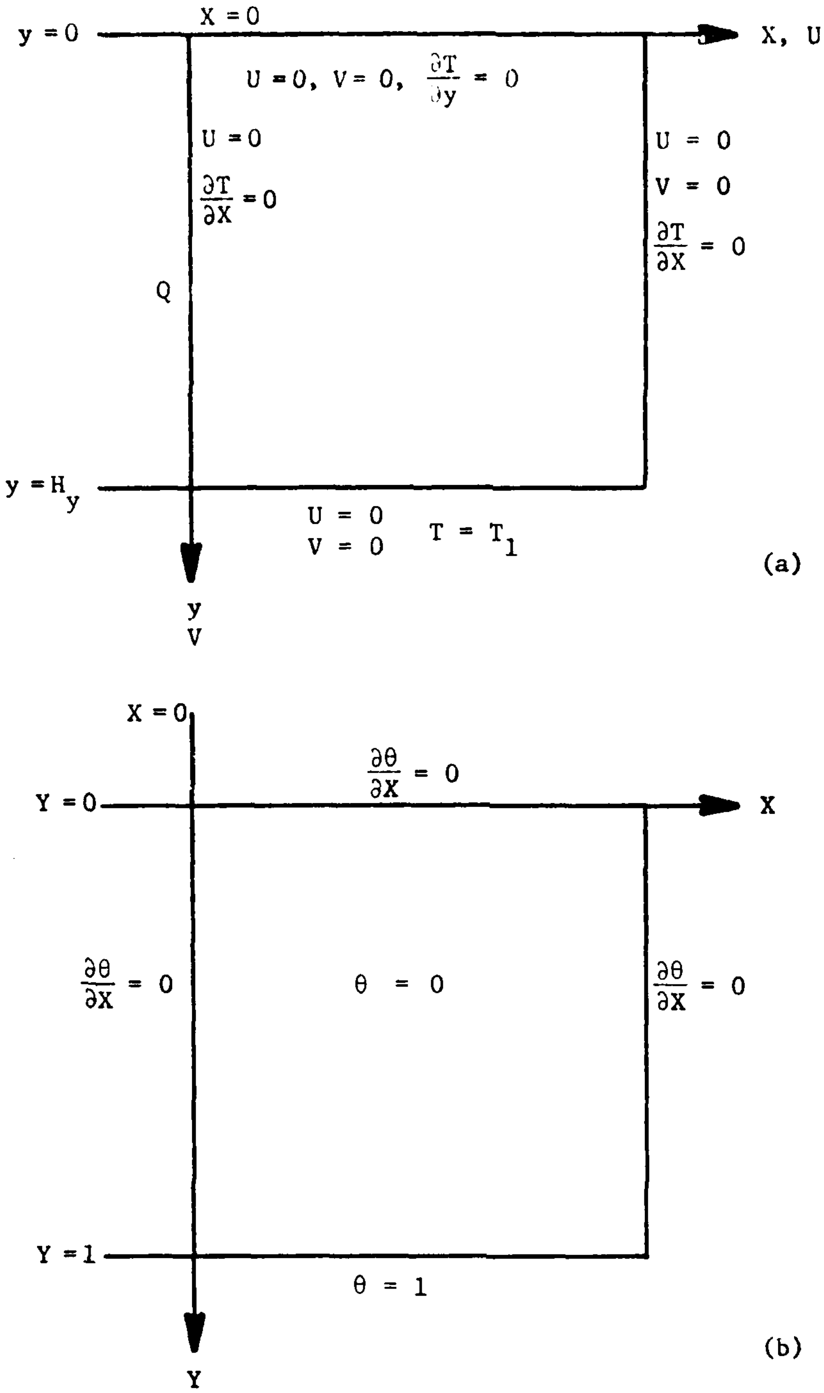


Figure 9. Computational domain with initial and boundary conditions in (a) dimensional form; (b) non-dimensional form.

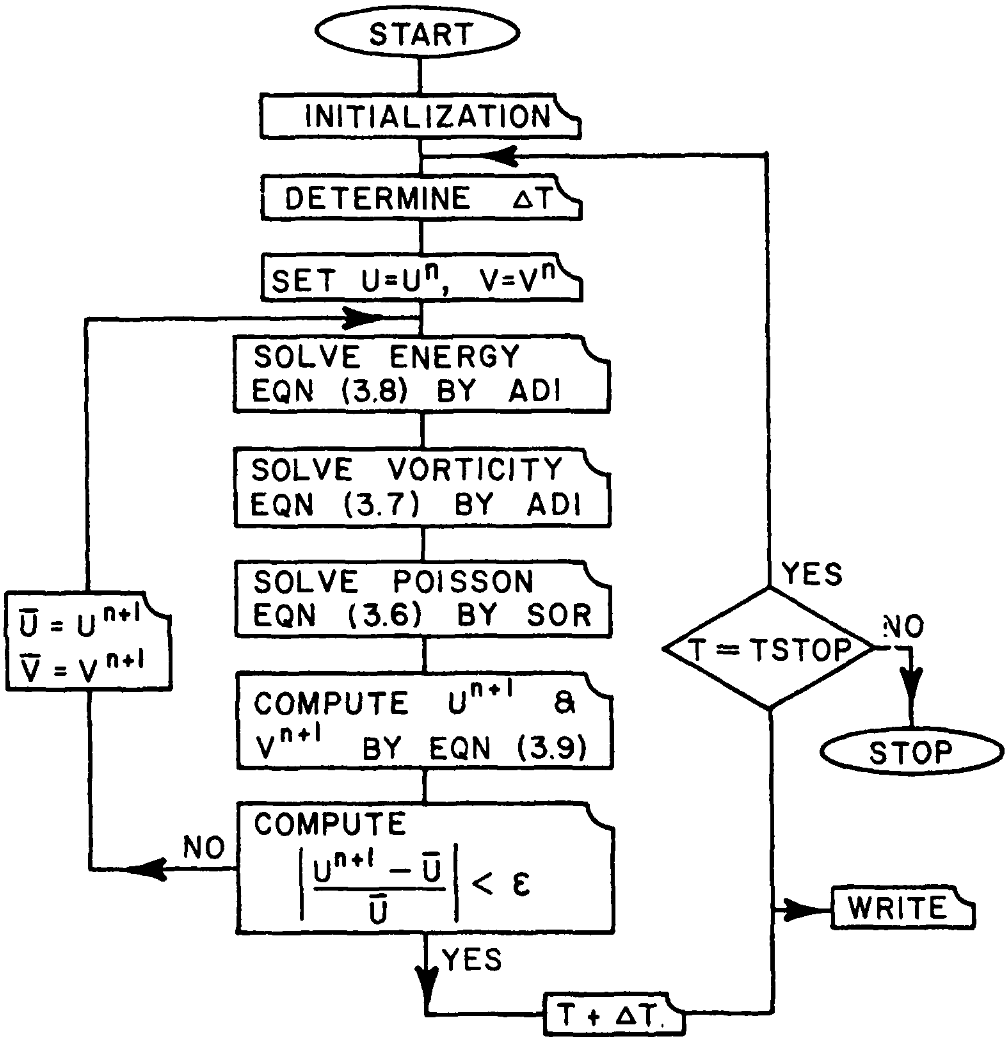


Fig. 10. FLOW DIAGRAM

$$\frac{\theta^{n+1}_{i,j} - \theta^{*}_{i,j}}{\Delta\tau/2} + \frac{(U\theta)^{*}_{i+1,j} - (U\theta)^{*}_{i-1,j}}{2\,\Delta X} + \frac{(V\theta)^{n+1}_{i,j+1} - (V\theta)^{n+1}_{i,j-1}}{2\Delta Y}$$

$$= \frac{1}{P_r}\left[\frac{\theta^{*}_{i+1,j} + \theta^{*}_{i-1,j} - 2\theta^{*}_{i,j}}{(\Delta X)^2} + \frac{(V\theta)^{n+1}_{i,j+1} - (V\theta)^{n+1}_{i,j-1}}{(\Delta Y)^2}\right]$$

$$+ \frac{1}{P_r} Q^{*}_{i,j} \tag{3.11}$$

Equations (3.10) and (3.11) can be solved by a tri-diagonal matrix solver, such as Thomas algorithm.

The vorticity equation (3.7) is then solved by exactly the same method with $\theta^{n+1}_{i,j}$ values. After this, equation (3.6) is then solved by SOR technique, i.e., with $\Delta X = \Delta Y$,

$$\psi^{(m+1)}_{i,j} = (1-\omega)\,\psi^{(m)}_{i,j} + \frac{\omega}{4}\Big[(\Delta X)^2\,\Omega^{n+1}_{i,j} + \psi^{m}_{i+1,j} + \psi^{m+1}_{i-1,j} + \psi^{m}_{i,j+1} + \psi^{m+1}_{i,j-1}\Big] \tag{3.12}$$

where ω is a relaxation parameter. A new velocity is then computed by equation (3.9). New approximation with

$$V^{*} = \frac{1}{2}\,(U^{n} + V^{n+1}) \quad \text{and} \quad V^{*} = \frac{1}{2}\,(V^{n+1} + V^{n})$$

is made until there is no appreciable change in U^{n+1} and V^{n+1}. This process is to be continued until the computation progresses to a designated run time.

3.3 SIMULATION TESTS AND RESULTS

Simulation test runs have been made for conductive and convective heating utilizing horizontal and vertical heating sources in a 400' x 400' x 50' tank (1.42 million barrels). Heating source temperatures up to 346°C (655°F) and heating times up to 30 hours were investigated. At 655°F, the No. 6 fuel oil would undergo cracking [2] even for short periods of heating. A more realistic heating temperature of 150°C (320°F) for longer periods of heating was also investigated. Simulation times are related to computer use time and were limited by funding constraints of this investigation.

3.3.1 CONDUCTION MODEL

(i) Horizontal Heaters

Horizontal heating of No. 6 fuel oil is probably the most used method by industry of heating stored No. 6 fuel oil. Therefore, the temperature profiles shown in Figures 11 and 12 are of prime interest as they represent those conditions that might be experienced under the RPR storage program. In accordance with RPR criteria, concept design is based on a withdrawal temperature of 49^{o}C (120^{o}F) and all pumping horsepower requirements on a No. 6 fuel oil viscosity at this temperature. For a 150^{o}C (302^{o}F) heating medium and with the heat of fusion of the wax crystals considered, Figure 12 shows that 120^{o}F or greater might be expected up to about 12 inches. For a 45-day draw-down schedule, approximately 10 inches would be removed from the storage tank each day. From these data it may be determined that the No. 6 fuel oil outside the heat exchanger tubes is near the same temperature as the heating medium inside the tubes. Thus, the use of a large heat transfer area is required. For example, if the estimated 28^{o}F delta temperature is valid, a heat exchanger having the equivalent of 70,000 feet of standard 2-inch pipe would be required.

(ii) Vertical Heaters

Figures 13 and 14 show the temperature profiles obtained by a vertical heater. For conductive heating alone, the vertical heating appears less desirable than horizontal heating.

$\lambda = 0.063$ Btu/hr ft °F $\quad \rho = 63.4$ lbm/ft^3

$c_v = 0.46$ Btu/lbm °F $\quad \nu_0 = 5 \times 10^{-4}$ ft^2/sec

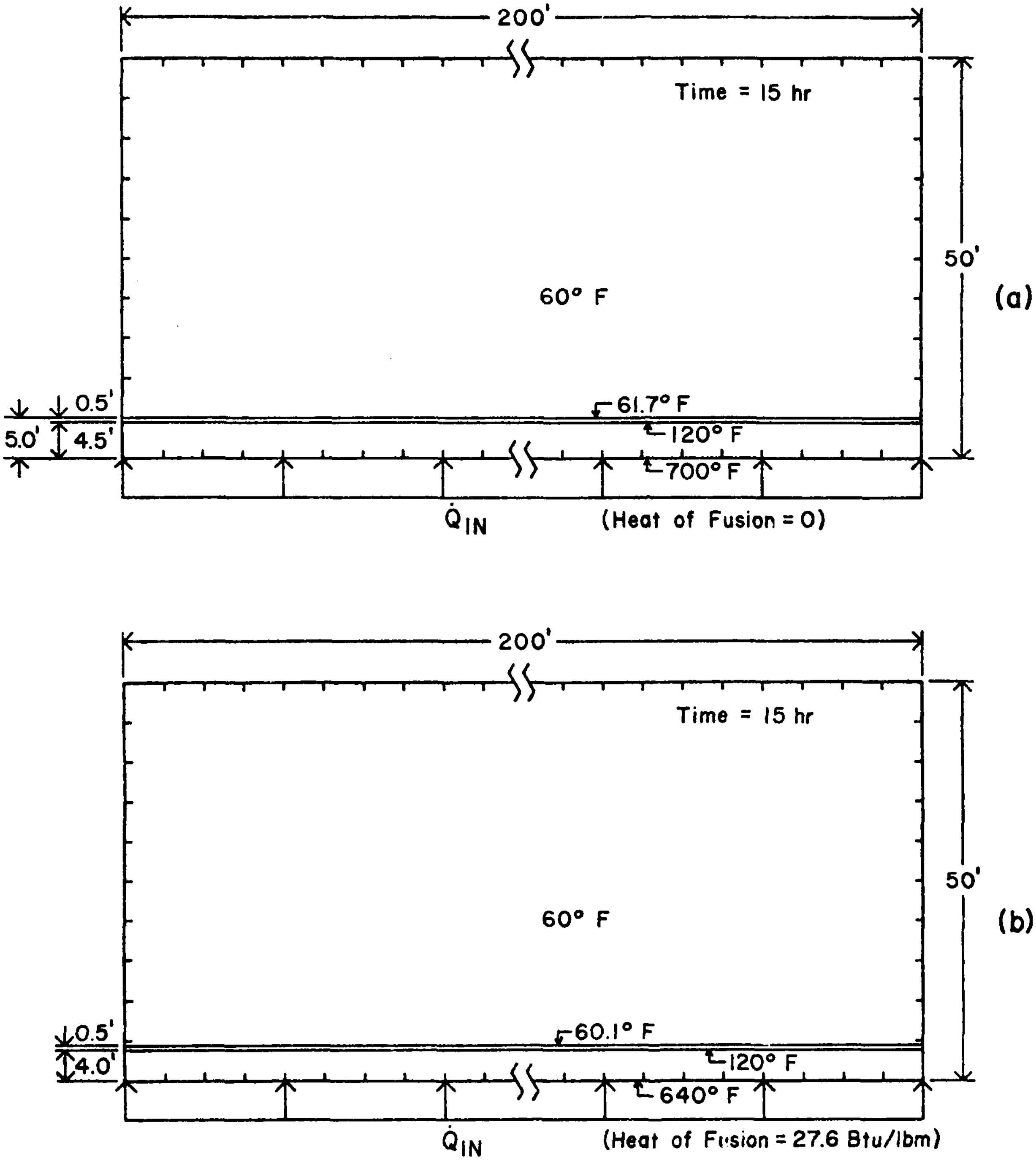


FIG. 11. CONDUCTION WITH HORIZONTAL HEATER

(Case A, $\dot{Q}_{IN} = 5.25 \times 10^3$ Btu/hr ft^3)

$\lambda = 0.063$ Btu/hr ft °F $\quad \rho = 63.4$ lbm/ft^3

$c_v = 0.46$ Btu/lbm °F $\quad \nu_0 = 5 \times 10^{-4}$ ft^2/sec

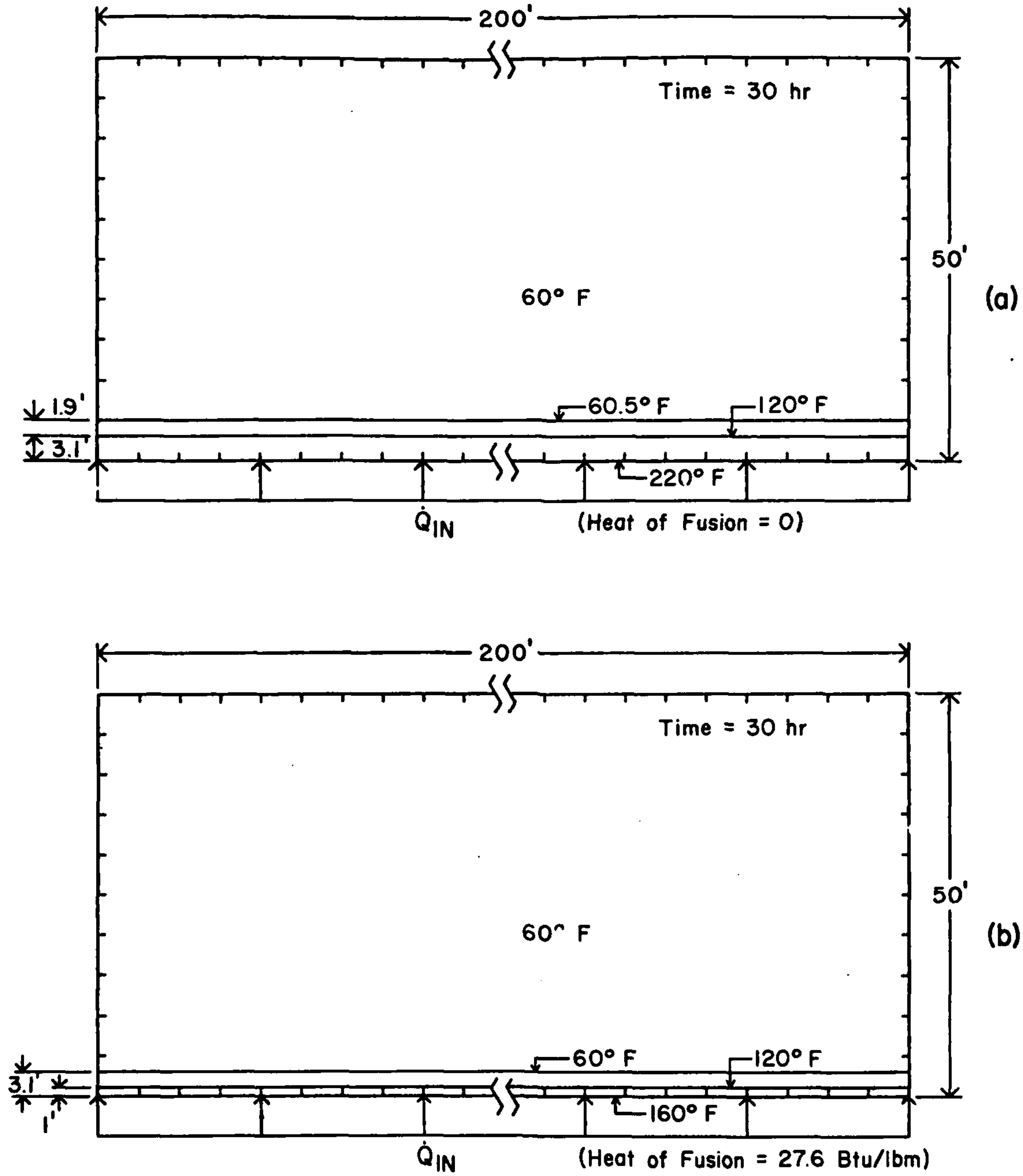


FIG. 12. CONDUCTION WITH HORIZONTAL HEATER

(Case B, $\dot{Q}_{IN} = 2 \times 10^2$ Btu/hr ft^3)

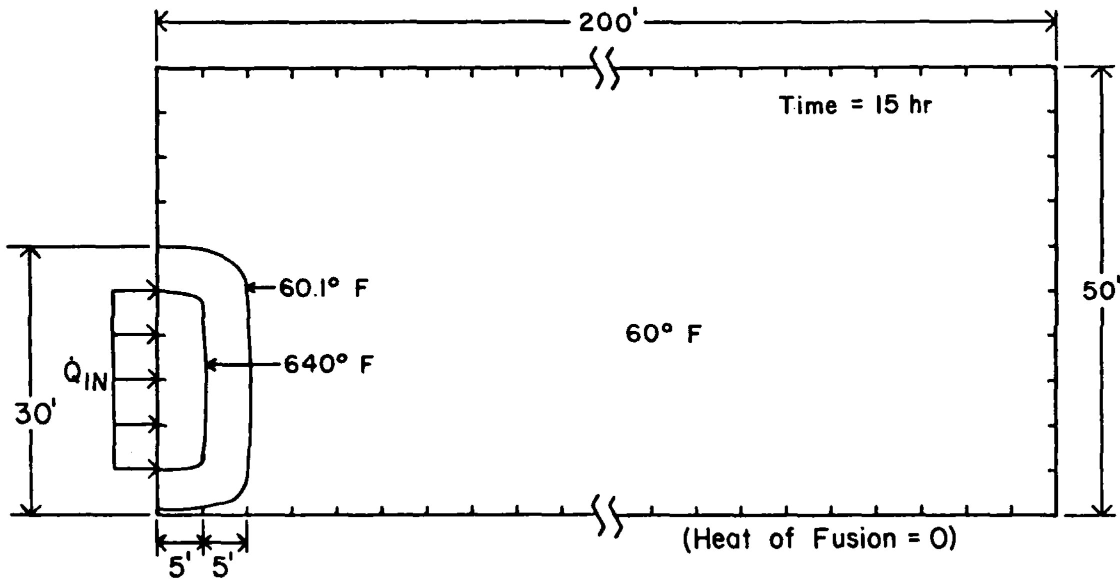


FIG. 13. CONDUCTION WITH VERTICAL HEATER

(Case A, $\dot{Q}_{IN}$ = 5.25 x 10^3 Btu/hr ft^3)

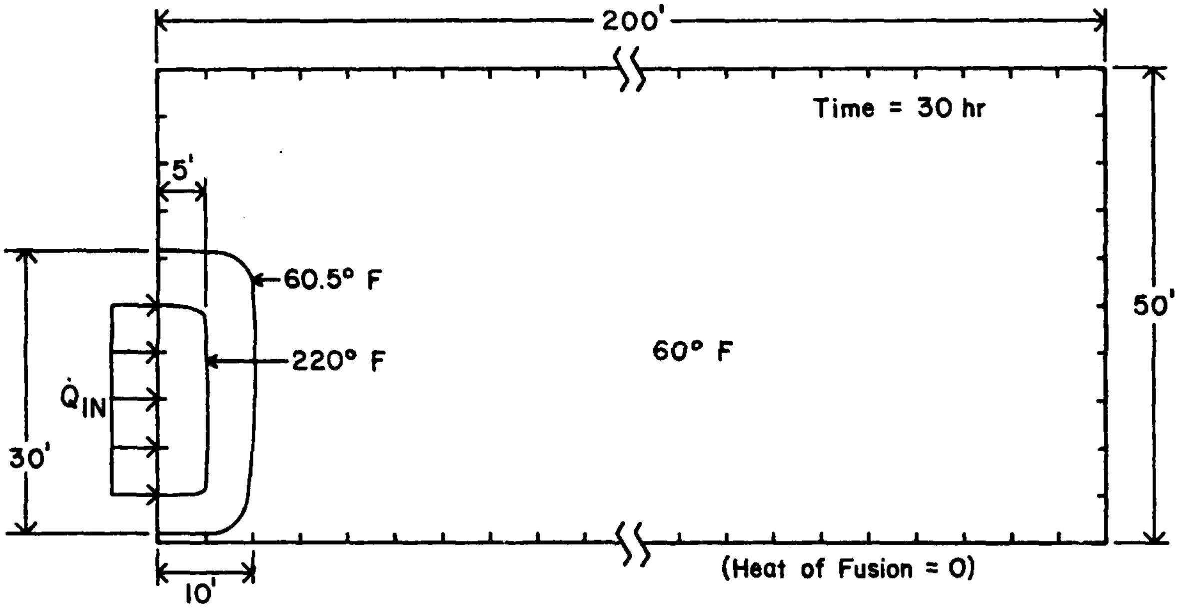


FIG. 14. CONDUCTION WITH VERTICAL HEATER
(Case B, $\dot{Q}_{IN} = 2 \times 10^2$ Btu/hr ft^3)

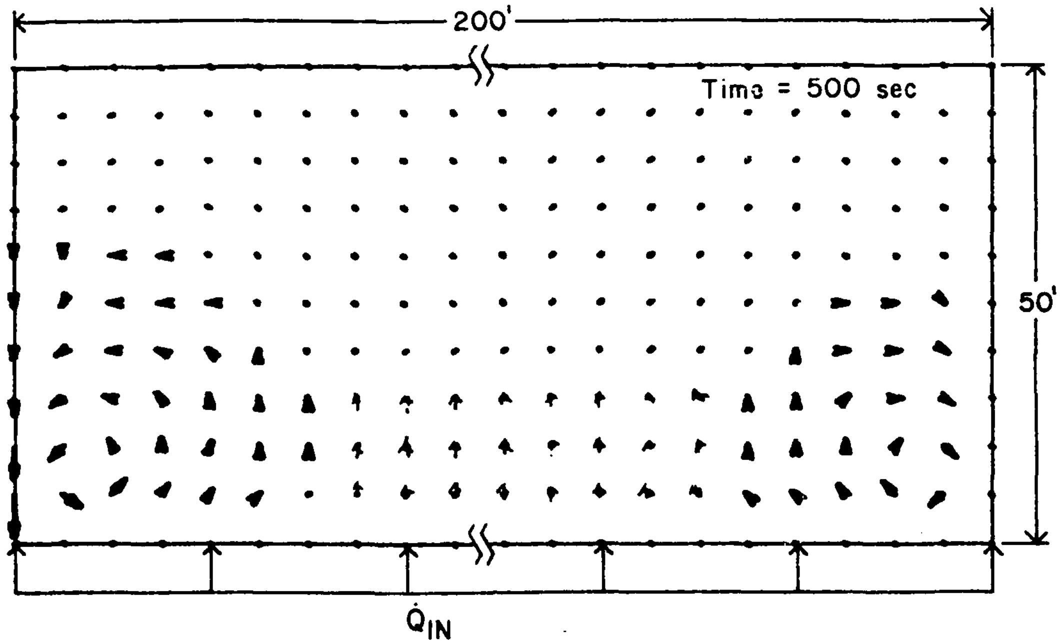
3.3.2 CONVECTION MODEL

(i) Horizontal Heaters

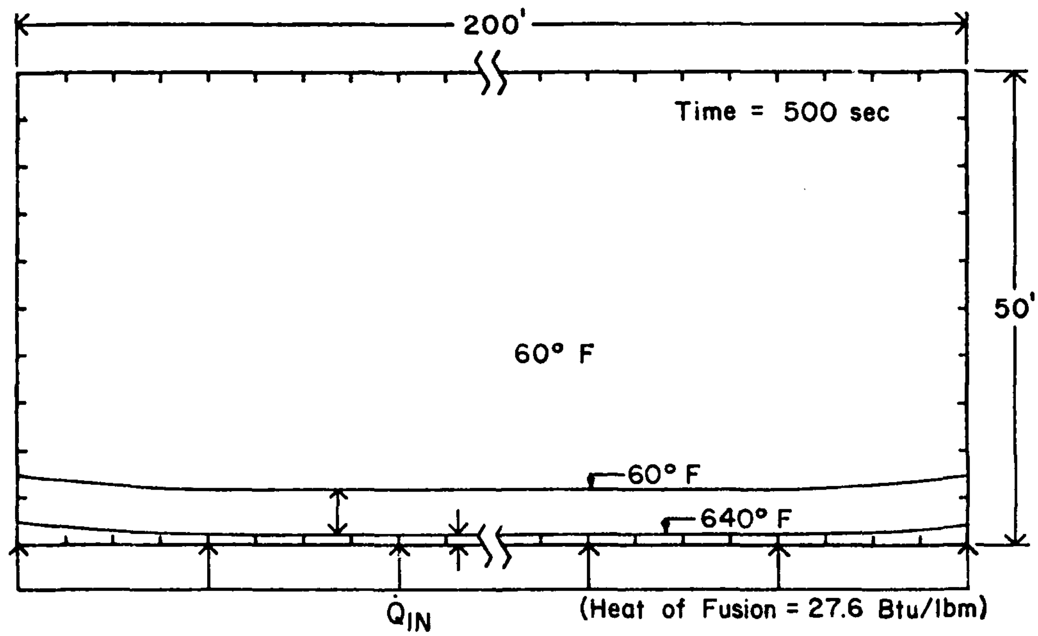
Figures 15 and 16 show the velocity vector displays and temperature distributions within the storage tank at 500 seconds after activation of the horizontal heater. The rates of heat supplied are 1.6×10^3 and 2×10^2 Btu/ft^3/hr, respectively. From this model calculation, the induced convective motions are very slow, only $\sim 1.44 \times 10^{-6}$ and 9.12×10^{-7} ft/sec, respectively. These velocities are so low that they would not significantly increase the overall heat transfer coefficient across the heat exchange tubes. The temperature distributions are also depicted in Figures 15 and 16. Because the effects of fusion and temperature dependence of transport coefficients are not included, the temperature profile shown in the figures are approximately 60°F too high.

(ii) Vertical Heaters

Figures 17 and 18 show the velocity vector displays and temperature distributions within the storage tank after the vertical heater has been turned on. These velocities are in the order of 2×10^2 times as great as they were for the horizontal heating cases. However, they still remain extremely low. The heat supply rate is the same as for the horizontal heater, but the total amount of heat added is smaller because the heating surface is much smaller. Thus, the volume of the heated oil is only 2×10^3 cubic feet.



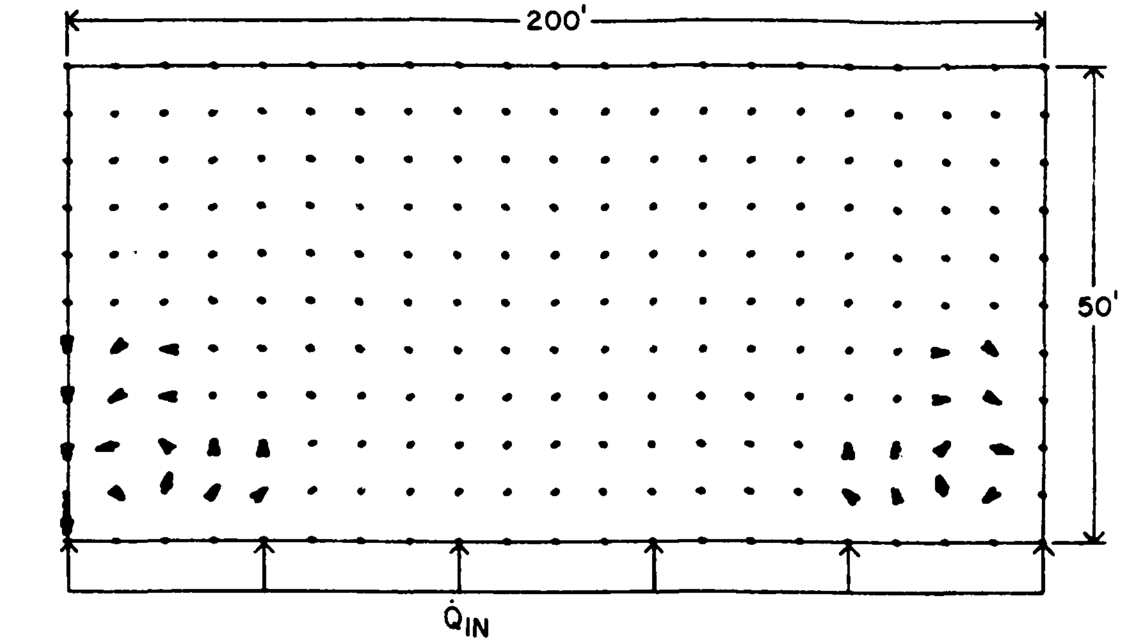
VELOCITY PROFILE ($|\underset{\sim}{V}|_{max} = 1.44 \times 10^{-6}$ ft/sec)



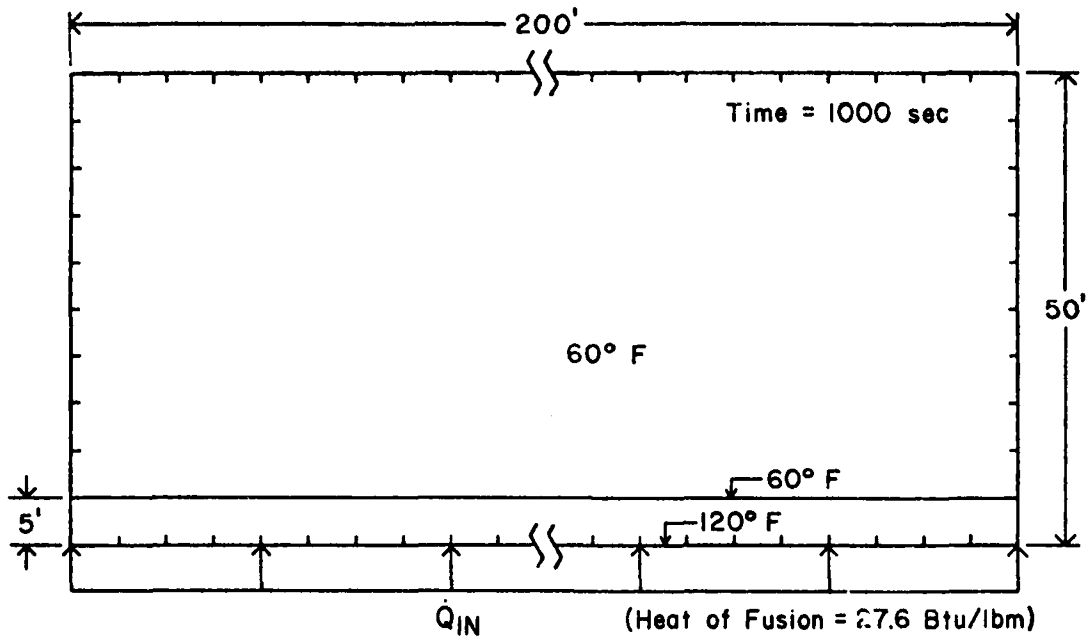
TEMPERATURE PROFILE

FIG. 15. CONVECTION WITH HORIZONTAL HEATER

(Case A, $\dot{Q}_{IN} = 1.6 \times 10^3$ Btu/hr ft^3)



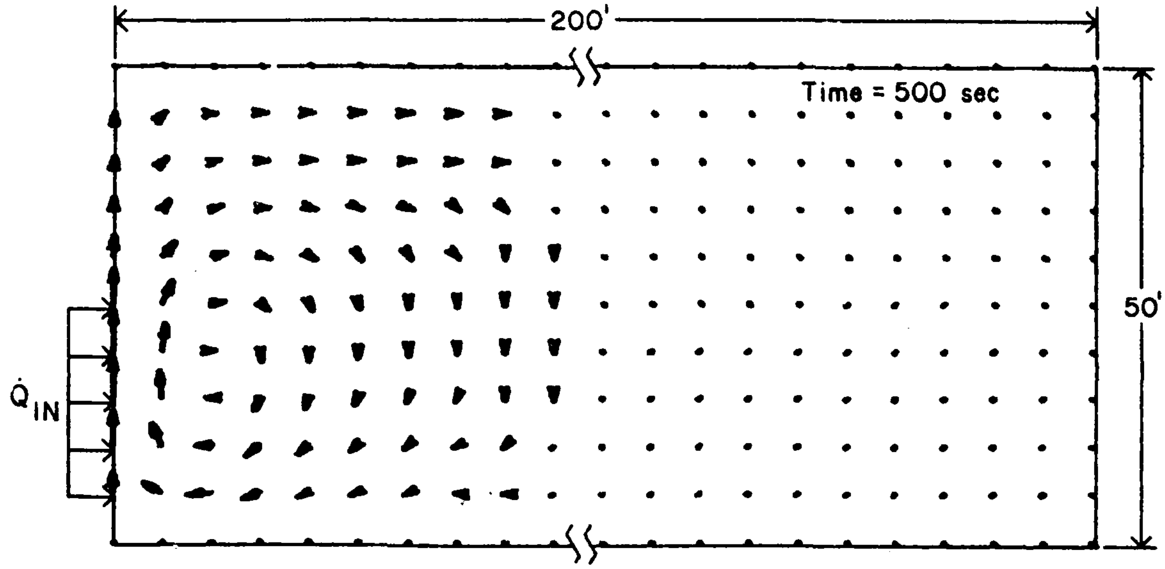
VELOCITY PROFILE ($|V|_{max} = 9.12 \times 10^{-7}$ ft/sec)



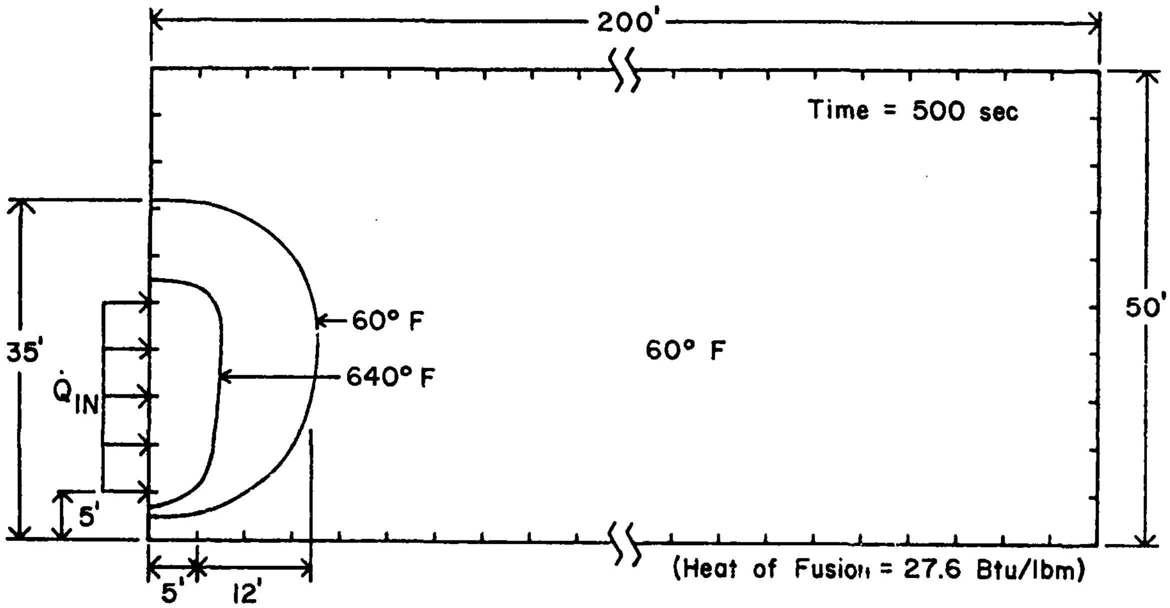
TEMPERATURE PROFILE

FIG. 16. CONVECTION WITH HORIZONTAL HEATER

(Case B, $\dot{Q}_{IN} = 2 \times 10^{2}$ Btu/hr ft^{3})



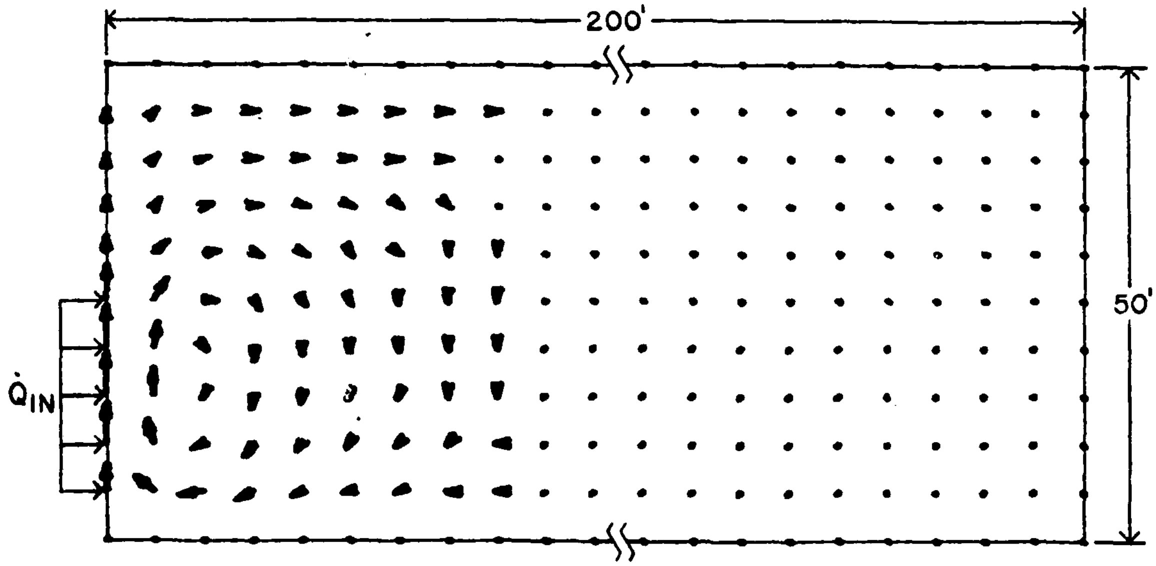
VELOCITY PROFILE ($|\underset{\sim}{V}|_{max}$ = 3×10^{-4} ft/sec)



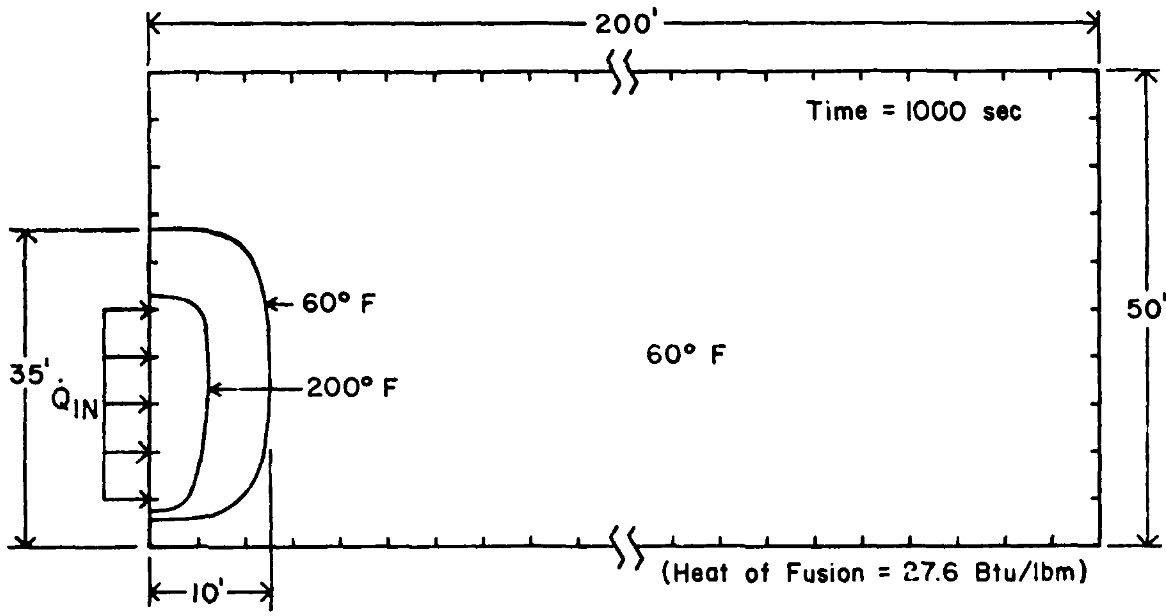
TEMPERATURE PROFILE

FIG. 17. CONVECTION WITH VERTICAL HEATER

(Case A, $\dot{Q}_{IN} = 1.6 \times 10^3$ Btu/hr ft^3)



VELOCITY PROFILE ($|V|_{max} = 1.73 \times 10^{-4}$ ft/sec)



TEMPERATURE PROFILE

FIG. 18. CONVECTION WITH VERTICAL HEATER
(Case B, $\dot{Q}_{IN} = 2 \times 10^2$ Btu/hr ft^3)

SECTION 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 Thermodynamic properties for No. 6 oil are almost non-existent. For analysis purposes, they have to be estimated from similar petroleum products.

4.2 Convective heating is much more effective than conductive heating of No. 6 fuel oil as its viscosity rapidly decreases as its temperature increases. Two non-dimensional parameters, i.e.,

$$Gr = g\beta \; \Delta\theta H_y^2/\nu_o^2 \qquad \text{(Grashof number)}$$

and

$$Pr = \mu C_p/\lambda \qquad \text{(Prandtl number)}$$

determine the characteristics of convective flow motion and consequently convective heat transfer rate. As viscosity decreases Grashof number increases quadratically and stronger convection current will develop as seen from equation (3.7). Reduced viscosity makes the Prandtl number smaller and consequently higher heat transfer rate as seen from equation (3.8).

4.3 Fluid motions for a vertical heater induces velocities approximately 2×10^2 times higher than those of the horizontal heater and they take place throughout a larger volume of the oil.

4.4 Industry practice of keeping stored No. 6 fuel oil in a hot liquid state appears to be justified. Allowing it to cool and congeal

prior to heating and withdrawal presents extensive technical risks that should not be taken unless substantiated by experimental data. Thus, recommend that RPR No. 6 fuel oil storage criteria be modified to allow No. 6 fuel oil to be heated sufficiently to keep all its components in a liquid state during storage.

4.5 If paragraph (4) above is not adapted, it is recommended that longer simulation tests be performed; present data indicates that prolonged heating (two weeks) prior to withdrawal may not be the optimum preheating time.

4.6 If paragraph (4) above is not adapted, it is recommended that inches of drawdown per day be considered in the determination of the storage tanks dimensions.

4.7 Additional larger scale active storage studies are recommended to verify results of this analysis, and to provide management with factual data to substantiate an ultimate decision on whether to heat the stored product, or not.

REFERENCES

[1] Silla, Harry, Switching Fuel Oils During a National Emergency, Tech. Rept. Stevens Institute of Technology, Hoboken, N.J., December 1977.

[2] Goodger, E. M., Hydrocarbon Fuels, Production, Properties and Performance of Liquids and Gases, Halstead Book, John Wiley & Sons, New York, 1975.

[3] Nelson, W. L., Petroleum Refinery Engineering, McGraw Hill, New York, 1936.

[4] Bai, S. D., Private Communication, Houston, Texas.

[5] Storage Tank Guide, Standard Oil Company.

[6] Cross, Ray, A Handbook of Petroleum, Asphalt and National Gas, Kansas City Testing Laboratory, 1931.

[7] Spiers, Ed, Technical Data on Fuel.

APPENDIX A

COMPUTER LISTING

APPENDIX A

COMPUTER LISTING

```
C
C      THIS PROGRAM STUDIES TWO DIMENSIONAL TIME DEPENDENT  FREE
C      CONVECTION IN A RECTANGULAR TANK.
C      IMPORTANT PHYSICAL PARAMETERS ARE GRASHOF AND PRANDTLE NUMBERS.
C      UNKNOWN VARIABLES ARE VORTICITY,TEMPERATURE AND STREAM FUNCTION
C      PRANDTLE NUMBER=PR
C      GRASHOF NUMBER=GR
C      VORTICITY=OMEGA,OMNEW,OME
C      TEMPERATURE=THETA,THET,THNEW
C      STREAM FUNCTION=PSI
C      VELOCITY IN X-DIRECTION=U,UNEW
C      VELOCITY IN Y-DIRECTION=V,VNEW
C
C
       PARAMETER  M=21,N=11
       DIMENSION U(M,N),V(M,N),OMEGA(M,N),THETA(M,N),PSI(M,N),RHS(M,N),
      1UNEW(M,N),VNEW(M,N),OMNEW(M,N),THNEW(M,N),HAU(M,N),HAV(M,N),
      2HAT(M,N),OME(M,N),THET(M,N),S(M,N),A(M,N),B(M,N),C(M,N),
      3W(M,N),BETA(M,N),GAMMA(M,N),INQ(M,N)
       DATA  PR,GR/8.0,1000.0/
       DATA  DT,MAXSTP,ERRMAX,MAXKDI/0.0005,20,0.001,10/
       DATA  IPLT/ 5/
C
       VM=  0.
       MM=M-1
       NN=N-1
       H=1.0/(N-1.0)
       GR=-GR
       NSTEP=0
       TIME=0.0
C      SPECIFY INITIAL FLOW (U,V) ,TEMPERATURE FIELD(THETA) AND HEAT
C      SOURCE(INQ)
       DO 1 I=1,M
       DO 1 J=1,N
       U(I,J)=0.0
       V(I,J)=0.0
       OMEGA(I,J)=0.0
       THETA(I,J)=0.0
    1  IF(J .EQ. N)  THETA(I,J)=1.0
       DO 2 I=1,M
       DO 2 J=1,N
    2  INQ(I,J)=0
       DO 3 I=1,M
       INQ(I,NN)=1000
    3  INQ(I,N)=1000
C
C      PROCEED TO NEXT TIME LEVEL AND COMPUTE TEMPERATURE,VORTICITY AND
C      VELOCITY AT THE NEW TIME LEVEL
C
 2000  NSTEP=NSTEP+1
       IF(NSTEP .GT. MAXSTP) GO TO 100
       TIME=TIME+DT
       DO 10 I=1,M
       DO 10 J=1,N
       UNEW(I,J)=U(I,J)
       VNEW(I,J)=V(I,J)
       OMNEW(I,J)=OMEGA(I,J)
```

```
   10  THNEW(I,J)=THETA(I,J)
C
C      ENERGY EQUATION IS SOLVED HERE . ADI METHOD IS EMPLOYED.
C      OLD TIME LEVEL VELOCITIES ARE USED.
C      RESULTING TRI-DIAGONAL MATRIX FROM ADI METHOD ARE SOLVED BY
C      PULL-PUSH METHOD IN X-DIRECTION (TRIDG1) AND Y-DIPECTION (TRIDG2).
C
       KDI=1
       R=DT/(PR*H*H)
       RR=DT/H
 1000  DO 21 J=2,NN
       DO 21 I=2,MM
       HAU(I,J)=(U(I,J)+UNEW(I,J))/4.0
       HAV(I,J)=V(I,J)/2.0
       A(I,J)=-(HAU(I,J)*RR+R)
       B(I,J)=2.0*(1+R)
       C(I,J)=HAU(I,J)*RR-R
       S(I,J)=2.0*THETA(I,J)-HAV(I,J)*RR*(THETA(I,J+1)-THETA(I,J-1))
      A+R*(THETA(I,J+1)-2.0*THETA(I,J)+THETA(I,J-1))
      B+R*H*H*INQ(I,J)
       IF(I-2) 15,13,15
   13  B(2,J)=B(2,J)+4.0*A(2,J)/3.0
       C(2,J)=C(2,J)-A(2,J)/3.0
   15  IF (I-MM) 19,17,19
   17  A(MM,J)=A(MM,J)-C(MM,J)/3.0
       B(MM,J)=B(MM,J)+4.0*C(MM,J)/3.0
   19  CONTINUF
   21  CONTINUE
       DO 22 I=1,M
       DO 22 J=1,N
       THET(I,J)=THETA(I,J)
   22  HAT(1,J)=THETA(I,J)
       DO 23 J=2,NN
       CALL   TRIDG1(J,M,N,A,B,C,S,W,BETA,GAMMA)
       DO 23 I=2,MM
       THET(I,J)=W(I,J)
   23  HAT(I,J)=W(I,J)
       DO 25 J=2,NN
       THET(1,J)=(4.0*THET(2,J)-THET(3,J))/3.0
   25  THET(M,J)=(4.0*THET(M-1,J)-THET(M-2,J))/3.0
       DO 35 I=2,MM
       DO 35 J=2,NN
       HAV(I,J)=VNEW(I,J)/2.0
       A(I,J)=-(HAV(I,J)*RR+R)
       B(I,J)=2.0*(1+R)
       C(I,J)=HAV(I,J)*RR-R
       S(I,J)=2.0*THET(I,J)-HAU(I,J)*RR*(THET(I+1,J)-THET(I-1,J))
      A+R*(THET(I+1,J)-2.0*THET(I,J)+THET(I-1,J))
      B+R*H*H*INQ(I,J)
       IF (J-2) 29,27,29
   27  B(I,2)=B(I,2)+4.0*A(I,2)/3.0
       C(I,2)=C(I,2)-A(I,2)/3.0
   29  IF (J-NN) 33,31,33
   31  S(I,NN)=S(I,NN)-C(I,NN)
   33  CONTINUE
   35  CONTINUE
       DO 37 I=2,MM
```

```
      CALL  TRIDG2(I,M,N,A,B,C,S,W,BETA,GAMMA)
      DO 37 J=2,NN
   37 THET(I,J)=W(I,J)
      DO 38 I=1,M
   38 THET(I,1)=(4.0*THET(I,2)-THET(I,3))/3.0
      DO 39 J=2,NN
      THET(1,J)=(4.0*THET(2,J)-THET(3,J))/3.0
   39 THET(M,J)=(4.0*THET(M-1,J)-THET(M-2,J))/3.0
C
C     VORTICITY EQUATION IS SOLVED BY ADI METHOD WITH JUST COMPUTED
C     TEMPERATURE FIELD AND OLD TIME LEVEL VELOCITIES (U,V)
C
      R1=DT/(H*H)
      DO 40 I=1,M
      DO 40 J=1,N
   40 OME(I,J)=(OMEGA(I,J)+OMNEW(I,J))/2.0
      DO 49 J=2,NN
      DO 49 I=2,MM
      A(I,J)=-(HAU(I,J)*RR+R1)
      B(I,J)=2.0*(1+R1)
      C(I,J)=HAU(I,J)*RR-R1
      S(I,J)=2.0*OMEGA(I,J)-0.5*V(I,J)*RR*(OMEGA(I,J+1)
     A-OMEGA(I,J-1))+R1*(OMEGA(I,J+1)-2.0*OMEGA(I,J)
     A+OMEGA(I,J-1))+0.5*GR*RR*(HAT(I+1,J)-HAT(I-1,J))
      IF (I-2) 43,41,43
   41 S(2,J)=S(2,J)
   43 IF(I-MM) 47,45,47
   45 S(MM,J)=S(MM,J)-C(MM,J)*(-4.0*V(MM,J)+V(MM-1,J))/(2.0*H)
   47 CONTINUE
   49 CONTINUE
      DO 51 J=2,NN
      CALL  TRIDG1(J,M,N,A,B,C,S,W,BETA,GAMMA)
      DO 51 I=2,MM
   51 OME(I,J)=W(I,J)
      DO 63 I=2,MM
      DO 63 J=2,NN
      A(I,J)=-(HAV(I,J)*RR+R1)
      B(I,J)=2.0*(1+R1)
      C(I,J)=HAV(I,J)*RR-R1
      S(I,J)=2.0*OME(I,J)-HAU(I,J)*RR*(OME(I+1,J)-OME(I-1,J))
     A+R1*(OME(I+1,J)-2.0*OME(I,J)+OME(I-1,J))
     A+0.5*GR*RR*(HAT(I+1,J)-HAT(I-1,J))
      IF (J-2) 57,55,57
   55 S(I,2)=S(I,2)-A(I,2)*(-4.0*U(I,2)+U(I,3))/(2.0*H)
   57 IF (J-NN) 61,59,61
   59 S(I,NN)=S(I,NN)-C(I,NN)*(4.0*U(I,NN)-U(I,NN-1))/(2.0*H)
   61 CONTINUE
   63 CONTINUE
      DO 65 I=1,M
      DO 65 J=1,N
   65 OME(I,J)=OMNEW(I,J)
      DO 67 I=2,MM
      CALL  TRIDG2(I,M,N,A,B,C,S,W,BETA,GAMMA)
      DO 67 J=2,NN
   67 OME(I,J)=W(I,J)
      DTMAX=0.0
      DOMAX=0.0
```

```
C
C     COMPUTE THE STREAM FUNCTION BASED ON COMPUTED VORTICITY FIELD
C     BY SUCCESSIVE OVERRELAXATION METHOD( CALL SUBROUTINE SORLX)
C
      DO 69 I=1,M
      DO 69 J=1,N
   69 RHS(I,J)=-OME(I,J)
      CALL  SORLX(PSI,RHS,M,N,H,0.0001,ITER)
C
C     COMPUTE UAND V AT INTERIOR POINTS AND AT THE AXIS OF SYMMETRY
C
      DO 71 I=2,MM
      DO 71 J=2,NN
      UNEW(I,J)=(PSI(I,J+1)-PSI(I,J-1))/(2.0*H)
   71 VNEW(I,J)=-(PSI(I+1,J)-PSI(I-1,J))/(2.0*H)
      DO 72 J=2,NN
      UNEW(1,J)=0.0
   72 VNEW(1,J)=-PSI(2,J)/H
C
C     COMPUTE VORTICITY AT SOLID WALLS USING U AND V.
C
      DO 74 J=2,NN
      OME(1,J)=0.0
   74 OME(M,J)=(-4.0*VNEW(MM,J)+VNEW(MM-1,J))/(2.0*H)
      DO 76 I=1,M
      OME(I,1)=(-4.0*UNEW(I,2)+UNEW(I,3))/(2.0*H)
   76 OME(I,N)=(4.0*UNEW(I,N-1)+UNEW(I,N-2))/(2.0*H)
C
C     SUM OF DIFFERRENCE BETWEEN THE RESULTS OF TWO SUCCESSIVE CAL-
C     CULATION FOR VORTICITY AND TEMPERATURE MUST BE LESS THAN ERRMAX.
C     IF NOT, ITERATION CONTINUES...
C
      DO 77 I=2,MM
      DO 77 J=2,NN
      OMED=ABS(OME(I,J)-OMNEW(I,J))
      IF (OMED .LE. DOMAX) GO TO  73
      DOMAX=OMED
   73 THED=ABS(THET(I,J)-THNEW(I,J))
      IF (THED .LE. DTMAX) GO TO  75
      DTMAX=THED
   75 CONTINUE
   77 CONTINUE
      WRITE(6,78) KDI,DOMAX,DTMAX
   78 FORMAT(1X,4HKDI=,I4,3X,6HDOMAX=,F9.6,3X,6HDTMAX=,F9.6)
      IF ((DTMAX+DOMAX) .LE. ERRMAX) GO TO  81
      DO 79 I=2,MM
      DO 79 J=2,NN
      THNEW(I,J)=THET(I,J)
   79 OMNEW(I,J)=OME(I,J)
      KDI=KDI+1
      IF (KDI .GT. MAXKDI) GO TO  81
      GO TO 1000
   81 DO 83 I=1,M
      DO 83 J=1,N
      THETA(I,J)=THET(I,J)
      OMEGA(I,J)=OME(I,J)
      U(I,J)=UNEW(I,J)
```

```
 83   V(I,J)=VNEW(I,J)
C
      IF(NSTEP.EQ.1)  GO TO 7000
      IF(NSTEP.GE.MAXSTP)  GO TO 7000
      IF(MOD(NSTEP,IPLT).NE.0)  GO TO 7020
 7000 CONTINUE
      DO 7010 I=1,M
      DO 7010 J=1,N
      VMAG=  SQRT(U(I,J)**2 +V(I,J)**2)
 7010 VM=  AMAX1(VMAG,VM)
      MT=  M
      NT=  N
      WRITE(10)  TIME,VM,MT,NT,((U(I,J),V(I,J),I=1,M),J=1,N)
C
 7020 CONTINUE
      WRITE(6,86) TIME
  86  FORMAT(/5X,5HTIME=,F10.5)
      WRITE(6,80)
  80  FORMAT(/5X,4HPSI=)
      WRITE(6,82)  ((PSI(I,J),J=1,N,2),I=1,M)
  82  FORMAT(/11(1X,F10.6))
      WRITE(6,84)
  84  FORMAT(/5X,6HOMEGA=)
      WRITE(6,85)  ((OMEGA(I,J),J=1,N,2),I=1,M)
  85  FORMAT(/11(1X,F10.6))
      WRITE(6,87)
  87  FORMAT(/5X,6HTHETA=)
      WRITE(6,88)  ((THETA(I,J),J=1,N,2),I=1,M)
  88  FORMAT(/11(1X,F10.6))
      WRITE(6,89)
  89  FORMAT(/5X,2HU=)
      WRITE(6,90)  ((U(I,J),J=1,N,2),I=1,M)
  90  FORMAT(/11(1X,F10.6))
      WRITE(6,91)
  91  FORMAT(/5X,2HV=)
      WRITE(6,92)  ((V(I,J),J=1,N,2),I=1,M)
  92  FORMAT(/11(1X,F10.6))
      GO TO 2000
 100  STOP
      END

OMPILATION:        NO  DIAGNOSTICS.
```

```
      SUBROUTINE  SORLX(F,Q,M,N,H,ERRMAX,ITER)
      DIMENSION F(M,N),Q(M,N)
      MM=M-1
      NN=N-1
      PI=4.0*ATAN(1.0)
      ALPHA=COS(PI/M)+COS(PI/N)
      OPTOM=(8.0-4.0*SQRT(4.0-ALPHA**2))/ALPHA**2
      ITER=0
      DO 101 I=1,M
      DO 101 J=1,N
  101 F(I,J)=0.0
  107 ITER=ITER+1
      ERROR=0.0
      DO 109 I=2,MM
      DO 109 J=2,NN
      FOLD=F(I,J)
      F(I,J)=F(I,J)+0.25*OPTOM*(F(I-1,J)+F(I+1,J)+F(I,J-1)
     A+F(I,J+1)-4.0*F(I,J)-H*H*Q(I,J))
  109 ERROR=ERROR+ABS(F(I,J)-FOLD)
      IF (ERROR .GT. ERRMAX)  GO TO 107
      RETURN
      END

      SUBROUTINE  TRIDG1(J,M,N,A,B,C,D,W,BETA,GAMMA)
      DIMENSION A(M,N),B(M,N),C(M,N),D(M,N),W(M,N),BETA(M,N),GAMMA(M,N)
      MM=M-1
      BETA(2,J)=B(2,J)
      GAMMA(2,J)=D(2,J)/BETA(2,J)
      DO 301 K=3,MM
      BETA(K,J)=B(K,J)-A(K,J)*C(K-1,J)/BETA(K-1,J)
  301 GAMMA(K,J)=(D(K,J)-A(K,J)*GAMMA(K-1,J))/BETA(K,J)
      W(MM,J)=GAMMA(MM,J)
      L1=MM-2
      DO 302 K=1,L1
      LL=MM-K
  302 W(LL,J)=GAMMA(LL,J)-C(LL,J)*W(LL+1,J)/BETA(LL,J)
      RETURN
      END

      SUBROUTINE  TRIDG2(I,M,N,A,B,C,D,W,BETA,GAMMA)
      DIMENSION A(M,N),B(M,N),C(M,N),D(M,N),W(M,N),BETA(M,N),GAMMA(M,N)
      NN=N-1
      BETA(I,2)=B(I,2)
      GAMMA(I,2)=D(I,2)/BETA(I,2)
      DO 201 K=3,NN
      BETA(I,K)=B(I,K)-A(I,K)*C(I,K-1)/BETA(I,K-1)
  201 GAMMA(I,K)=(D(I,K)-A(I,K)*GAMMA(I,K-1))/BETA(I,K)
      W(I,NN)=GAMMA(I,NN)
      L1=NN-2
      DO 202 K=1,L1
      LL=NN-K
  202 W(I,LL)=GAMMA(I,LL)-C(I,LL)*W(I,LL+1)/BETA(I,LL)
      RETURN
      END
```

APPENDIX B

FEASIBILITY OF SOLAR ENERGY

FOR

HEATING RESIDUAL OIL STORAGE FACILITIES

May 30, 1980

Prepared For

U.S. ARMY CORP OF ENGINEERS
HUNTSVILLE, ALABAMA

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ABSTRACT

This report describes a study to determine the technical and economic feasibility of solar energy for long-term heating of stored residual fuel oil. Four sites along the East Coast were used as a basis for the evaluations: Portland, ME; New York, NY; Norfolk, VA; and Jacksonville, FL. Systems were sized for product temperatures of 90°F, 100°F, 110°F, and 120°F. The study considered storage of oil in aboveground tanks, belowground containers and in mines. A number of solar heating concepts were identified in the categories of active heating, passive heating, and heat pumps. Active heating systems are viable heating options for all conditions considered. Passive systems studied offered a definite cost advantage, but were not suited for the northernmost locations at the higher storage temperatures. Heat pump systems are an attractive alternative to conventional practice, particularly in terms of source energy consumed; but the cost will be site specific, depending upon the proximity of a waste heat source.

CHAPTER 1
INTRODUCTION

To reduce the impact of possible embargos on shipments of foreign oil, the Federal government initiated the establishment of strategic reserves capable of replacing energy imports. Consideration is being given to stockpiling a wide range of liquid fuels including crude, distillates, and residuals.

Studies of consumption and import patterns[1] indicate the East Coast as being the most dependent upon imported energy, and therefore, the area most vulnerable to an embargo. Because of the distance to low sulfur coal fields, it also has the greatest dependence upon residual fuel oil which is used as an energy source for electrical generating plants, for industrial processing, and for space heating.

Residual fuel oils have low vapor pressures and high pour points. The temperature range for solidification is $15^{o}F$ to $100^{o}F$ with the average being approximately $65^{o}F$. Therefore, when stored over a long term before extraction, it is reasonable to assume that partial or total solidification will occur with the process starting at the tank wall, floor, and liquid surface.

Two options are available for countering the solidification process, e.g., (1) maintaining the oil in a fluid condition and (2) heating the oil to fluid conditions only when embargo conditions occur. The first of these is not economical for long-term storage because of the high energy costs involved and the second presents unknown technical problems associated with heating of so large a mass of solid fuel to a fluid state for effective withdrawal.

Solar energy is a potentially effective alternative to conventional sources for providing heating necessary for long term storage of residual oil. Some of the potential benefits of solar for this application are:

- solar heating is environmentally benign
- since elevated temperature levels are maintained continuously withdrawal can be initiated without warmup delay
- costly heat exchangers may not be necessary
- no precious fossil fuels will be consumed during the storage interval or during the withdrawal under emergency embargo conditions

---

[1]"Investigation of Feasibility and Practicality of Using Aboveground Steel Tanks to Store a Strategic Reserve of Finished Petroleum Products", Van Houten Associates, New York, New York.

- little or no maintenance is required for well designed, properly installed systems
- potential for reduced land requirements compared to standby boilers and fuel storage
- favorable public attitudes, and
- moisture problems associated with vented-coned-roof tanks are potentially eliminated.

The heating of residual oil is an application which is ideally matched with the capabilities of solar because

- temperature requirements are well within the range of efficient operation of low cost flat plate collectors, and
- no solar storage system is required.

The principal limitation of solar is its high initial cost.

To evaluate the potential feasibility of solar energy for long term heating of residual fuel storage facilities, a study was undertaken with the following objectives.

- develop solar heating concepts for aboveground, belowground, and mine storage
- evaluate solar feasibility for four cities: Portland, Maine; New York, New York; Norfolk, Virginia; and Jacksonville, Florida
- estimate system cost for maintaining the stored material at temperatures of 120°F, 110°F, 100°F and 90°F
- analyze shading profiles of tanks, and
- identify important societal/environmental attitudinal aspects of solar.

In this study, a number of solar system concepts were defined for the three types of storage. The systems were categorized as active, passive, and heat pumps. Using estimates of system technical and economic characteristics, system studies were conducted to evaluate the relative merits of some selected concepts in each of the three categories. Finally, the active system was defined in some detail to permit a more accurate assessment of costs.

CHAPTER 2
SUMMARY AND CONCLUSIONS

Active solar heating systems using flat plate collectors were found to be technically feasible for maintaining residual oil at the extraction temperature for all sites, temperatures, and storage methods considered. Standard flat plate solar collectors which employ double-glazing, or selective surfaces, can be readily interfaced with heat exchangers currently employed with conventional oil heating plants; and can be considered for near term application requiring no extension of the commercialized state-of-the-art for either the petroleum related components or the solar related components. Conservative cost estimates of complete active solar systems for a full sized facility, including heat exchanger and tank insulation, ranged from $1.00 to $3.59 per barrel of product stored, depending upon location, climate, storage temperature, and collector placement. By comparison, the conventional oil-fired system is estimated to cost between $4.75 and $7.51 per barrel of stored product.

Passive systems are most attractive for aboveground storage, except at the higher storage temperatures and colder climates. However, the acrylic glazing material used as a basis for this study is not suitable as a skylight concept due to its flammability. For those conditions where the passive system was technically viable, costs ranged from $0.68 to $1.05 per barrel of stored product.

The heat pump can readily produce the required temperature when extracting heat from a variety of heat sources, including low temperature solar collection devices. In the one example considered, where the heat pump extracted waste heat from the condenser of a power plant, the heat pump was found to consume 90 percent to 158 percent less source energy than a boiler heating plant. Detailed heat pump system costs were not developed because of the site specific nature of this concept and the limited time available for the study.

Figure 2-1 summarizes the total system cost for each type of storage and solar system concept. Preliminary system costs for mine storage were found to be excessive because of the high heat loss associated with ground water heating. Therefore, these costs were not detailed further in the study.

As a result of the limited study conducted, the following conclusions were reached.

- Active solar systems are technically feasible for maintaining residual oil at extraction temperatures ranging from 90°F to 120°F.
- Active system costs range from $1.00 to $3.59 per barrel of product stored for aboveground and belowground cut-and-cover storage.

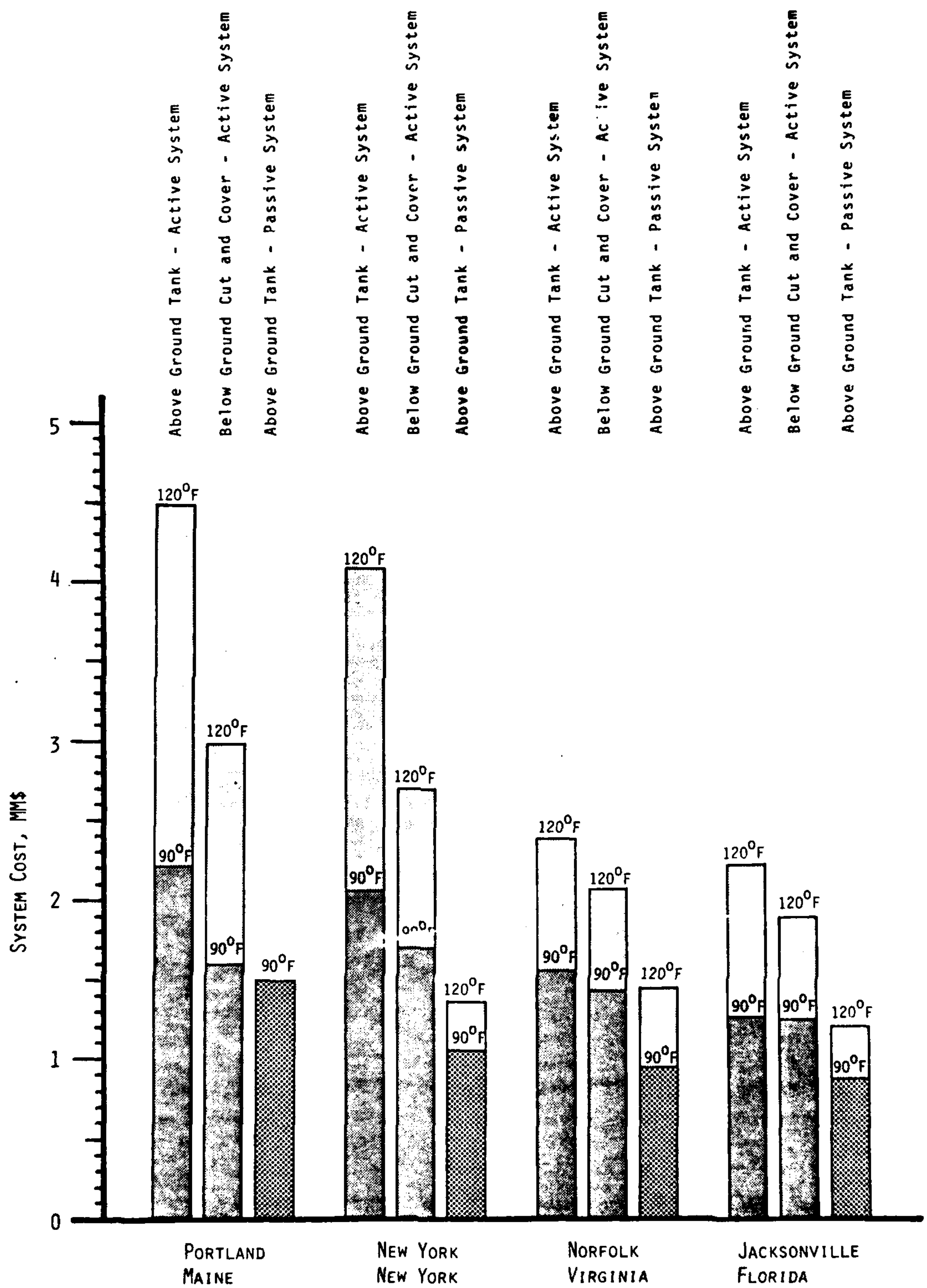

Figure 2-1. TOTAL SYSTEM COST PER TANK (1.25 MMB CAPACITY)

- System costs for mines appear to be excessive (roughly a factor of two greater than for tank storage).

- The optimum tank insulation thickness was identified as about three inches, taking into consideration the combined effects of heat production by solar and reduction of tank heat losses by insulation.

- Solar system cost is strongly dependent on temperature at which the product is stored. For example, the system cost can be reduced by more than a factor of two if $90^{o}F$ storage temperature is used rather than $120^{o}F$.

- Climate also strongly affects system cost, with Jacksonville requiring a system which is roughly one-half as expensive as for Portland.

- Passive systems are potentially less expensive than active systems and are considerably less complex mechanically, requiring no fluid transport system, heat exchanger, etc. However, the flammability issue of synthetic glazing material must be resolved.

- Technical feasibility of passive systems are highly dependent on climate and the temperature at which the product is stored. For example, passive heating is viable in Jacksonville at all storage temperatures considered, but in Portland passive heating is viable only at $90^{o}F$.

- Intermediate performance flat plate collectors employing selective surface and single-glazing (or perhaps flat black surface and double-glazing) are more cost effective than low performance flat black single-glazed collectors.

- Using simplified thermodynamic modeling, annual swings of $\pm 2^{o}F$ to $\pm 5^{o}F$ about the mean storage temperature can be expected.

- Heat pumps are an attractive alternative to boilers for heating the product immediately prior to storage. Economic viability may be dependent on proximity of the storage site to a waste heat source, such as cooling water discharged from the condenser of a power plant.

- Accurate methods of predicting heat loss is a requisite to minimized system cost. This is particularly true for below-ground cut-and-cover storage and mine storage systems (if they are considered further).

- Because of the sensitivity of solar collector performance to the return temperature of the heat transfer fluid, and

the large capital costs involved, the design optimization of active solar systems must concurrently consider the tank heat exchanger as well as the solar related subsystems.

- Since passive systems are incorporated into the tank structure, these systems will have the greatest impact on existing tank fabrication, erection, and logistical practices.

- Techniques employed for freeze protection of active solar collectors are compatible with existing heat exchanger configurations. No over-heat protection is required in this application of solar.

- The water bed heat exchanger is readily interfaced with active solar systems as the water can serve as the collector heat transfer fluid and the expense of a heat exchanger is eliminated.

- The tank roof is adequate for collector placement for all conditions examined except for Portland at product temperatures of 110°F and above.

In summarizing the conclusions from this study, it is clear that solar energy is a viable economic alternative to an oil-fired heating system. The cost of the solar system, even in the least favorable case examined, (e.g., Portland at 120°F) is almost one-half that of the oil-fired heating system. Since most of the solar concepts studied maintain the product at the desired extraction temperatures, (the exception is the heat pump) the technical uncertainty of liquifying a large solid mass in a short time period is avoided. Furthermore, solar heating is environmentally benign, thereby, avoiding unfavorable public attitudes associated with fossil heating plants.

The present study identified no significant barriers or limitations to the use of solar for heating of stored residual oil. Nevertheless, the study did indicate some areas that should be examined to assure that technical objectives of the Strategic Petroleum Reserve program can be met at a minimum cost. These areas are listed below.

- Identify passive glazing materials that are inflammable, but offer high performance, low cost, and good structural qualities. Design feasibility studies should be conducted.

- Conduct a detailed design evaluation of heat exchanger/collector concepts to identify optimized configurations and design parameters.

- Develop accurate models of ground heat loss to aid the sizing process.

- Other design concepts identified in the study but not considered in detail should be examined for technical and economic feasibility.

- An impact study should be conducted to determine the solar industry's capability for meeting the requirements for full scale deployment.
- One or more pilot scale storage and solar heating systems should be constructed and critically evaluated to establish confidence in solar energy as a viable alternative to boiler heating systems and to identify critical design, performance, fabrication and economic issues.
- The feasibility of storing the product at lower temperatures (i.e., 70-90^{o}F), should be examined, as this will reduce the total system cost.

CHAPTER 3
ENVIRONMENTAL DATA

An accurate accounting of the expected environmental characteristics of each site is critical to the estimation of solar system performance and to the determination of its requirements. In this section, the various parameters used in the study will be presented.

3.1 RADIATION DATA

In order to predict the performance of any solar conversion system, the diffuse and direct components of solar irradiation must be known on a temporal basis for the site in question. For the preliminary evaluations conducted in this report, monthly average radiation levels will permit sufficiently accurate performance estimates.

A second consideration in the determination of solar performance, is the prediction of radiation upon tilted surfaces. Although monthly averages of the daily solar radiation incident on a horizontal surface are available for many locations, radiation data on tilted surfaces are generally not available and must be estimated from horizontal values using theoretical methods.

The radiation values used in this study were provided courtesy of NASA's Marshall Space Flight Center. The computer codes developed by NASA are based on an extension of the method of Liu and Jordan[2] for estimating the average daily radiation on south facing surfaces. The extended method (Klein[3]) allows for estimation of the monthly average daily radiation on surfaces oriented east or west of south.

The procedure uses an ASHRAE[4] approach for determining hourly values of direct and diffuse radiation reaching the Earth's surface. A cloudiness factor for each site is applied to clear day total insolation to obtain the daily total for each month.

Tables 3-1 through 3-8 provide the radiation data used in the bulk of the study, e.g., radiation on a fixed surface tilted at the latitude of the site and oriented due south.

---

[2] Liu, B.Y.H. and Jordan, R.C., "Daily Insolation on Surfaces Tilted Toward The Equator," Trans ASHRAE, 526, (1962).

[3] Klein, S.A., "Calculation of Monthly Average Insolation on Tilted Surfaces," Solar Energy, Vol. 19, 325, (1977).

[4] "ASHRAE Handbook-1977 Fundamentals," American Society of Heating, Refrigeration and Air Conditioning Engineers, Inc.

Table 3-1. TOTAL SOLAR INSOLATION FOR FIXED POSITION COLLECTORS-BTU/SQFT-

SOLRAD DATA

Portland, Maine

LATITUDE- 43.6500 TILT- 43.6500 AZIMUTH- 0.0000

MONTHLY CLOUD COVER ADJUSTMENT VALUES ARE FOR CITY N 84

TIME	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
6AM	0.	0.	0.	11.	12.	13.	12.	11.	0.	0.	0.	0.
7AM	0.	3.	51.	69.	73.	73.	72.	68.	48.	3.	0.	0.
8AM	31.	107.	137.	144.	142.	140.	140.	141.	132.	103.	30.	3.
9AM	151.	194.	214.	212.	205.	200.	202.	207.	206.	189.	149.	122.
10AM	222.	257.	272.	266.	255.	248.	251.	259.	263.	251.	220.	201.
11AM	264.	296.	309.	300.	286.	278.	281.	292.	299.	289.	261.	244.
12PM	277.	309.	322.	311.	297.	288.	292.	304.	312.	302.	275.	259.
1PM	264.	296.	309.	300.	286.	278.	281.	292.	299.	289.	261.	244.
2PM	222.	257.	272.	266.	255.	248.	251.	255.	263.	251.	220.	201.
3PM	151.	194.	214.	212.	205.	200.	202.	207.	206.	189.	149.	122.
4PM	31.	107.	137.	144.	142.	140.	140.	141	132.	103.	30.	3.
5PM	0.	3.	51.	69.	73.	73.	72.	68.	48.	3.	0.	0.
6PM	0.	0.	0.	11.	12.	13.	12.	11.	0.	0.	0.	0.

MAXIMUM CLEAR AIR DAILY INSOLATION - BTU/SQFT

	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
DLYSM	1611.	2022.	2290.	2314.	2246.	2190.	2209.	2260.	2207.	1970.	1594.	1400.

MAXIMUM CLEAR AIR MONTHLY INSOLATION-BTU/SQFT

JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
49947.	56626.	70980.	69434.	69625.	65715.	68465.	70073.	662[illegible]8.	61083.	47824.	43395.

MAXIMUM YEARLY INSOLATION - BTU/SQFT - = 739385.

PROBABLE DAILY INSOLATION DUE TO CLOUD COVER

	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
DLYSM	725.	923.	1107.	1266.	1367.	1429.	1437.	1423.	1368.	1156.	736.	627.

PROBABLE MONTHLY INSOLATION DUE TO CLOUD COVER-BTU/SQFT

JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
22471.	25830.	34316.	37975.	42382.	42876.	44545.	44121.	41040.	35836.	22075.	19447.

PROBABLE YEARLY INSOLATION - BTU/SQFT - = 412916.

Table 3-2. TOTAL SOLAR INSOLATION FOR FIXED POSITION COLLECTORS-BTU/SQFT-

SOLRAD DATA New York, New York

LATITUDE= 40.7700 TILT= 40.7700 AZIMUTH= 0.0000

MONTHLY CLOUD COVER ADJUSTMENT VALUES ARE FOR CITY N 15E

TIME	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
6AM	0.	0.	0.	11.	13.	13.	13.	11.	0.	0.	0.	0.
7AM	0.	6.	54.	70.	73.	73.	72.	68.	50.	6.	0.	0.
8AM	56.	115.	140.	145.	143.	140.	141.	142.	135.	111.	55.	12.
9AM	164.	200.	217.	214.	206.	201.	203.	209.	209.	195.	162.	142.
10AM	232.	263.	276.	268.	256.	249.	252.	261.	267.	256.	230.	214.
11AM	273.	301.	313.	302.	288.	279.	283.	294.	303.	295.	270.	256.
12PM	286.	314.	325.	313.	298.	289.	293.	306.	315.	308.	284.	270.
1PM	273.	301.	313.	302.	288.	279.	283.	294.	303.	295.	270.	256.
2PM	232.	263.	276.	268.	256.	249.	252.	261.	267.	256.	230.	214.
3PM	164.	200.	217.	214.	206.	201.	203.	209.	209.	195.	162.	142.
4PM	56.	115.	140.	145.	143.	140.	141.	142.	135.	111.	55.	12.
5PM	0.	6.	54.	70.	73.	73.	72.	68.	50.	6.	0.	0.
6PM	0.	0.	0.	11.	13.	13.	13.	11.	0.	0.	0.	0.

MAXIMUM CLEAR AIR DAILY INSOLATION - BTU/SQFT

DLYSM	1738.	2085.	2323.	2331.	2255.	2198.	2218.	2276.	2241.	2032.	1719.	1517.

MAXIMUM CLEAR AIR MONTHLY INSOLATION-BTU/SQFT

53868.	58366.	72023.	69927.	69920.	65939.	68744.	70552.	67235.	63005.	51578.	47019.

MAXIMUM YEARLY INSOLATION - BTU/SQFT - = 758178.

PROBABLE DAILY INSOLATION DUE TO CLOUD COVER

DLYSM	850.	1042.	1264.	1408.	1474.	1509.	1542.	1540.	1502.	1304.	937.	762.

PROBABLE MONTHLY INSOLATION DUE TO CLOUD COVER-BTU/SQFT

26335.	29186.	39182.	42248.	45705.	45268.	47795.	47732.	45052.	40429.	28112.	23608.

PROBABLE YEARLY INSOLATION - BTU/SQFT - = 460654.

Table 3-3. TOTAL SOLAR INSOLATION FOR FIXED POSITION COLLECTORS-BTU/SQFT-
Norfolk, Virginia

SOLRAD DATA

LATITUDE= 36.9000 TILT= 36.9000 AZIMUTH= 0.0000

MONTHLY CLOUD COVER ADJUSTMENT VALUES ARE FOR CITY N 223

TIME	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
6AM	0.	0.	0.	11.	13.	13.	13.	11.	0.	0.	0.	0.
7AM	0.	13.	57.	70.	73.	72.	72.	68.	53.	11.	0.	0.
8AM	81.	124.	144.	147.	143.	140.	141.	143.	138.	120.	80.	52.
9AM	178.	207.	220.	216.	207.	202.	204.	211.	213.	202.	176.	161.
10AM	243.	269.	279.	270.	257.	250.	253.	263.	270.	263.	241.	228.
11AM	283.	308.	317.	304.	289.	280.	284.	296.	306.	301.	280.	268.
12PM	296.	321.	329.	316.	300.	291.	295.	308.	319.	314.	293.	282.
1PM	283.	308.	317.	304.	289.	280.	284.	296.	306.	301.	280.	268.
2PM	243.	269.	279.	270.	257.	250.	253.	2[illegible]3.	270.	263.	241.	228.
3PM	178.	207.	220.	216.	207.	202.	204.	2[illegible].	213.	202.	176.	161.
4PM	81.	124.	144.	147.	143.	140.	141.	1[illegible]3.	138.	120.	80.	52.
5PM	0.	13.	57.	70.	73.	72.	72.	63.	53.	11.	0.	0.
6PM	0.	0.	0.	11.	13.	13.	13.	11.	0.	0.	0.	0.
MAXIMUM CLEAR AIR DAILY INSOLATION - BTU/SQFT												
DLYSM	1867.	2162.	2363.	2350.	2266.	2206.	2227.	2293.	2281.	2107.	1847.	1699.
MAXIMUM CLEAR AIR MONTHLY INSOLATION-BTU/SQFT												
	57868.	60542.	73241.	70489.	70240.	66170.	69044.	71096.	61419.	65324.	55424.	52683.
MAXIMUM YEARLY INSOLATION - BTU/SQFT - = 780540.												
PROBABLE DAILY INSOLATION DUE TO CLOUD COVER												
DLYSM	992.	1180.	1433.	1628.	1651.	1697.	1627.	1615.	1575.	1426.	1227.	994.
PROBABLE MONTHLY INSOLATION DUE TO CLOUD COVER-BTU/SQFT												
	30757.	33040.	44437.	48840.	51172.	50905.	50423.	50077.	47240.	44192.	36824.	30806.
PROBABLE YEARLY INSOLATION - BTU/SQFT - = 518714.												

Table 3-4. TOTAL SOLAR INSOLATION FOR FIXED POSITION COLLECTORS-BTU/SQFT-
Jacksonville, Florida

SOLRAD DATA

LATITUDE= 30.5000 TILT= 30.5000 AZIMUTH= 0.0000

MONTHLY CLOUD COVER ADJUSTMENT VALUES ARE FOR CITY N 40

TIME	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
6AM	0.	0.	0.	11.	13.	13.	13.	11.	0.	0.	0.	0.
7AM	1.	32.	60.	70.	72.	71.	71.	68.	57.	30.	1.	0.
8AM	107.	135.	148.	148.	144.	140.	141.	144.	143.	131.	106.	91.
9AM	195.	216.	225.	218.	209.	203.	205.	213.	218.	211.	193.	182.
10AM	257.	278.	284.	273.	259.	251.	255.	266.	275.	271.	255.	245.
11AM	295.	316.	322.	307.	291.	282.	286.	299.	312.	309.	293.	283.
12PM	308.	329.	334.	319.	302.	292.	297.	311.	324.	322.	305.	296.
1PM	295.	316.	322.	307.	291.	282.	286.	299.	312.	309.	293.	283.
2PM	257.	278.	284.	273.	259.	251.	255.	266.	275.	271.	255.	245.
3PM	195.	216.	225.	218.	209.	203.	205.	213.	218.	211.	193.	182.
4PM	107.	135.	148.	148.	144.	140.	141.	144.	143.	131.	106.	91.
5PM	1.	32.	60.	70.	72.	71.	71.	68.	57.	30.	1.	0.
6PM	0.	0.	0.	11.	13.	13.	13.	11.	0.	0.	0.	0.
MAXIMUM CLEAR AIR DAILY INSOLATION - BTU/SQFT												
DLYSM	2017.	2281.	2415.	2373.	2277.	2213.	2237.	2315.	2333.	2225.	1998.	1897.
MAXIMUM CLEAR AIR MONTHLY INSOLATION-BTU/SQFT												
	62542.	63878.	74866.	71184.	70574.	66378.	69351.	71760.	69996.	68976.	59931.	58812.
MAXIMUM YEARLY INSOLATION - BTU/SQFT - = 808247.												
PROBABLE DAILY INSOLATION DUE TO CLOUD COVER												
DLYSM	1200.	1403.	1653.	1788.	1740.	1627.	1582.	1632.	1549.	1488.	1340.	1136.
PROBABLE MONTHLY INSOLATION DUE TO CLOUD COVER-BTU/SQFT												
	37189.	39270.	51242.	53651.	53947.	48804.	49852.	50580.	46464.	46114.	40188.	35210.
PROBABLE YEARLY INSOLATION - BTU/SQFT - = 551711.												

Table 3-5. TOTAL SOLAR INSOLATION FOR FIXED POSITION COLLECTORS-BTU/SQFT-Portland, Maine

SOLRAD DATA

LATITUDE= 43.6500 TILT= 0.0000 AZIMUTH= 0.0000

MONTHLY CLOUD COVER ADJUSTMENT VALUES ARE FOR CITY N 84

TIME	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
6AM	0.	0.	0.	23.	54.	67.	56.	24.	0.	0.	0.	0.
7AM	0.	3.	42.	86.	116.	127.	116.	86.	40.	3.	0.	0.
8AM	16.	58.	106.	147.	174.	182.	173.	146.	102.	57.	16.	4.
9AM	66.	113.	161.	200.	223.	230.	222.	198.	156.	111.	66.	47.
10AM	107.	156.	205.	241.	261.	267.	259.	237.	198.	154.	107.	87.
11AM	133.	184.	232.	265.	285.	290.	282.	262.	224.	180.	133.	112.
12PM	142.	193.	241.	275.	293.	297.	290.	271.	233.	189.	141.	121.
1PM	133.	184.	232.	266.	285.	290.	282.	262.	224.	180.	133.	112.
2PM	107.	156.	205.	241.	261.	267.	259.	237.	198.	154.	107.	87.
3PM	66.	113.	161.	200.	223.	230.	222.	198.	156.	111.	66.	47.
4PM	16.	58.	106.	147.	174.	182.	173.	146.	102.	57.	16.	4.
5PM	0.	3.	42.	86.	116.	127.	116.	86.	40.	3.	0.	0.
6PM	0.	0.	0.	23.	54.	67.	56.	24.	0.	0.	0.	0.

MAXIMUM CLEAR AIR DAILY INSOLATION - BTU/SQFT

DLYSM	787.	1222.	1732.	2204.	2519.	2621.	2504.	2179.	1671.	1201.	784.	622.

MAXIMUM CLEAR AIR MONTHLY INSOLATION-BTU/SQFT

24400.	34220.	53688.	66114.	78096.	78627.	77633.	67544.	58127.	37226.	23515.	19292.

MAXIMUM YEARLY INSOLATION - BTU/SQFT - = 610483.

PROBABLE DAILY INSOLATION DUE TO CLOUD COVER

DLYSM	449.	684.	970.	1300.	1562.	1704.	1653.	1460.	1153.	817.	455.	361.

PROBABLE MONTHLY INSOLATION DUE TO CLOUD COVER-BTU/SQFT

13908.	19163.	30065.	39007.	48420.	51107.	51238.	45255.	34588.	25313.	13639.	11190.

PROBABLE YEARLY INSOLATION - BTU/SQFT - = 382893.

Table 3-6. TOTAL SOLAR INSOLATION FOR FIXED POSITION COLLECTORS-BTU/SQFT-

New York, New York

SOLRAD DATA

LATITUDE= 40.7700 TILT= 0.0000 AZIMUTH= 0.0000

MONTHLY CLOUD COVER ADJUSTMENT VALUES ARE FOR CITY N 156

TIME	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
6AM	0.	0.	0.	21.	50.	62.	51.	22.	0.	0.	0.	0.
7AM	0.	6.	45.	87.	114.	124.	114.	87.	43.	6.	0.	0.
8AM	25.	67.	112.	151.	175.	182.	174.	149.	108.	66.	25.	11.
9AM	79.	125.	170.	206.	227.	232.	225.	203.	165.	123.	79.	61.
10AM	123.	170.	215.	248.	266.	271.	264.	245.	208.	167.	122.	103.
11AM	150.	198.	244.	275.	291.	295.	288.	271.	236.	195.	149.	130.
12PM	159.	208.	253.	284.	300.	303.	297.	280.	245.	204.	158.	139.
1PM	150.	198.	244.	275.	291.	295.	288.	271.	236.	195.	149.	130.
2PM	123.	170.	215.	248.	266.	271.	264.	245.	208.	167.	122.	103.
3PM	79.	125.	170.	206.	227.	232.	225.	203.	165.	123.	79.	61.
4PM	25.	67.	112.	151.	175.	182.	174.	149.	108.	66.	25.	11.
5PM	0.	6.	45.	87.	114.	124.	114.	87.	43.	6.	0.	0.
6PM	0.	0.	0.	21.	50.	62.	51.	22.	0.	0.	0.	0.

MAXIMUM CLEAR AIR DAILY INSOLATION - BTU/SQFT

DLYSM	914.	1342.	1827.	2260.	2546.	2636.	2529.	2231.	1764.	1318.	909.	748.

MAXIMUM CLEAR AIR MONTHLY INSOLATION-BTU/SQFT

28328.	37567.	56649.	67797.	78924.	79072.	78385.	69175.	52916.	40845.	27277.	23197.

MAXIMUM YEARLY INSOLATION - BTU/SQFT - = 640133.

PROBABLE DAILY INSOLATION DUE TO CLOUD COVER

DLYSM	548.	792.	1115.	1446.	1680.	1792.	1770.	1584.	1288.	949.	591.	456.

PROBABLE MONTHLY INSOLATION DUE TO CLOUD COVER-BTU/SQFT

16997.	22165.	34556.	43390.	52090.	53769.	54870.	49114.	38629.	29408.	17730.	14150.

PROBABLE YEARLY INSOLATION - BTU/SQFT - = 426868.

Table 3-7. TOTAL SOLAR INSOLATION FOR FIXED POSITION COLLECTORS-BTU/SQFT-
Norfolk, Virginia

SOLRAD DATA

LATITUDE= 36.9000 TILT= 0.0000 AZIMUTH= 0.0000

MONTHLY CLOUD COVER ADJUSTMENT VALUES ARE FOR CITY N 223

TIME	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
6AM	0.	0.	0.	18.	44.	55.	45.	18.	0.	0.	0.	0.
7AM	0.	12.	49.	87.	112.	120.	112.	86.	46.	12.	0.	0.
8AM	39.	78.	120.	154.	175.	182.	174.	153.	115.	77.	39.	24.
9AM	97.	140.	182.	213.	230.	235.	228.	210.	175.	137.	96.	79.
10AM	143.	188.	229.	258.	272.	275.	269.	253.	222.	184.	142.	124.
11AM	172.	218.	259.	286.	298.	301.	295.	281.	251.	214.	171.	152.
12PM	182.	228.	269.	295.	307.	309.	304.	290.	261.	224.	181.	162.
1PM	172.	218.	259.	286.	298.	301.	295.	281.	251.	214.	171.	152.
2PM	143.	188.	229.	258.	272.	275.	269.	253.	222.	184.	142.	124.
3PM	97.	140.	182.	213.	230.	235.	228.	210.	175.	137.	96.	79.
4PM	39.	78.	120.	154.	175.	182.	174.	153.	115.	77.	39.	24.
5PM	0.	12.	49.	87.	112.	120.	112.	86.	46.	12.	0.	0.
6PM	0.	0.	0.	18.	44.	55.	45.	18.	0.	0.	0.	0.

MAXIMUM CLEAR AIR DAILY INSOLATION - BTU/SQFT

DLYSM	1082.	1498.	1947.	2325.	2570.	2644.	2550.	2292.	1881.	1470.	1075.	920.

MAXIMUM CLEAR AIR MONTHLY INSOLATION-BTU/SQFT

33536.	41956.	60366.	69749.	79680.	79314.	79041.	71050.	56417.	45585.	32264.	28530.

MAXIMUM YEARLY INSOLATION - BTU/SQFT - = 677488.

PROBABLE DAILY INSOLATION DUE TO CLOUD COVER

DLYSM	682.	929.	1285.	1674.	1876.	2009.	1861.	1673.	1392.	1088.	807.	626.

PROBABLE MONTHLY INSOLATION DUE TO CLOUD COVER-BTU/SQFT

21127.	26013.	39842.	50220.	58166.	60279.	57700.	51866.	41749.	33733.	24198.	19400.

PROBABLE YEARLY INSOLATION - BTU/SQFT - = 484293.

Table 3-8. TOTAL SOLAR INSOLATION FOR FIXED POSITION COLLECTORS-BTU/SQFT-

Jacksonville, Florida

SOLRAD DATA

LATITUDE= 30.5000 TILT= 0.0000 AZIMUTH= 0.0000

MONTHLY CLOUD COVER ADJUSTMENT VALUES ARE FOR CITY N 40

TIME	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
6AM	0.	0.	0.	12.	33.	42.	34.	13.	0.	0.	0.	0.
7AM	1.	22.	55.	86.	106.	113.	105.	85.	52.	21.	1.	0.
8AM	61.	96.	131.	159.	174.	179.	173.	156.	127.	94.	61.	47.
9AM	125.	163.	198.	221.	233.	236.	231.	218.	191.	160.	124.	109.
10AM	174.	214.	249.	270.	279.	279.	275.	265.	241.	210.	173.	157.
11AM	206.	247.	282.	300.	307.	307.	303.	294.	273.	242.	204.	188.
12PM	217.	258.	293.	310.	317.	316.	313.	305.	283.	253.	215.	198.
1PM	206.	247.	282.	300.	307.	307.	303.	294.	273.	242.	204.	188.
2PM	174.	214.	249.	270.	279.	279.	275.	265.	241.	210.	173.	157.
3PM	125.	163.	198.	221.	233.	236.	231.	218.	191.	160.	124.	109.
4PM	61.	96.	131.	159.	174.	179.	173.	156.	127.	94.	61.	47.
5PM	1.	22.	55.	86.	106.	113.	105.	85.	52.	21.	1.	0.
6PM	0.	0.	0.	12.	33.	42.	34.	13.	0.	0.	0.	0.

MAXIMUM CLEAR AIR DAILY INSOLATION - BTU/SQFT

	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
DLYSM	1350.	1743.	2123.	2406.	2582.	2627.	2556.	2366.	2051.	1709.	1341.	1200.

MAXIMUM CLEAR AIR MONTHLY INSOLATION-BTU/SQFT

JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
41861.	48806.	65810.	72187.	80029.	78819.	79232.	73343.	61544.	52977.	40237.	37189.

MAXIMUM YEARLY INSOLATION - BTU/SQFT - = 732033.

PROBABLE DAILY INSOLATION DUE TO CLOUD COVER

	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
DLYSM	905.	1168.	1529.	1853.	1962.	1892.	1789.	1703.	1436.	1230.	993.	816.

PROBABLE MONTHLY INSOLATION DUE TO CLOUD COVER-BTU/SQFT

JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
28047.	32700.	47384.	55584.	60822.	56750.	55462.	52807.	43081.	38143.	29775.	25289.

PROBABLE YEARLY INSOLATION - BTU/SQFT - = 525843.

3.2 AMBIENT TEMPERATURES

In order to compute tank heat loss and solar collector performance, it is necessary to have available environmental temperatures for each of the sites. This data was taken from the Climatic Atlas[5] and is presented in Figures 3-1 through 3-12.

Also required for computation of solar system performance is atmospheric "clearness factors." Figures 3-13 presents profiles of these for the U.S.

3.3 SNOW AND WIND DATA

Snow and wind loads are required to size the collector mounting structure and to access the impact of roof mounted arrays on the tank structure. Table 3-9 presents this data, also taken from the Climatic Atlas.

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[5]"Climatic Atlas of the United States," U.S. Department of Commerce, Environmental Science Service Administration.

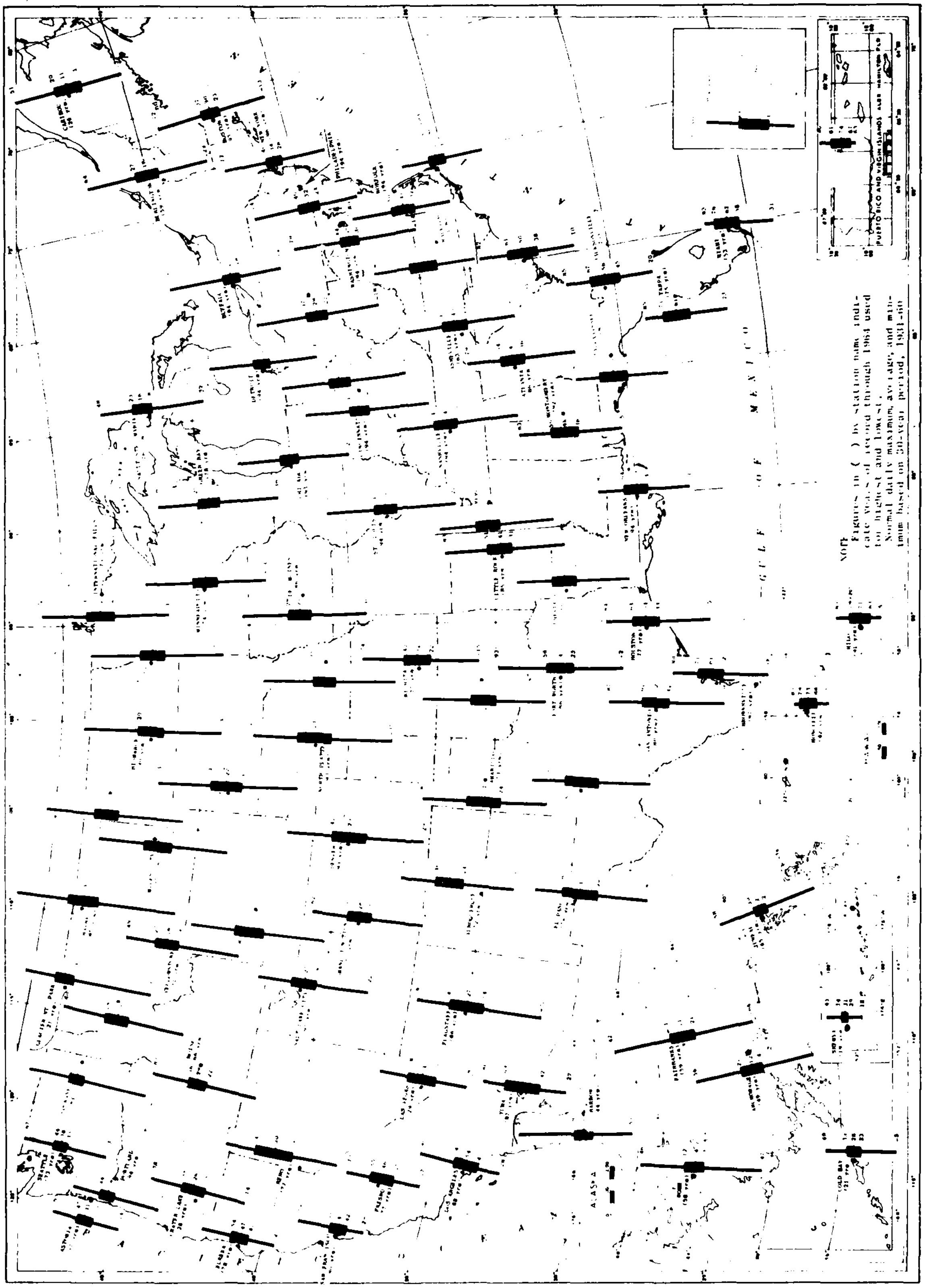

Figure 3-1. NORMAL DAILY MAXIMUM, AVERAGE, MINIMUM, AND EXTREME TEMPERATURES (°F), JANUARY

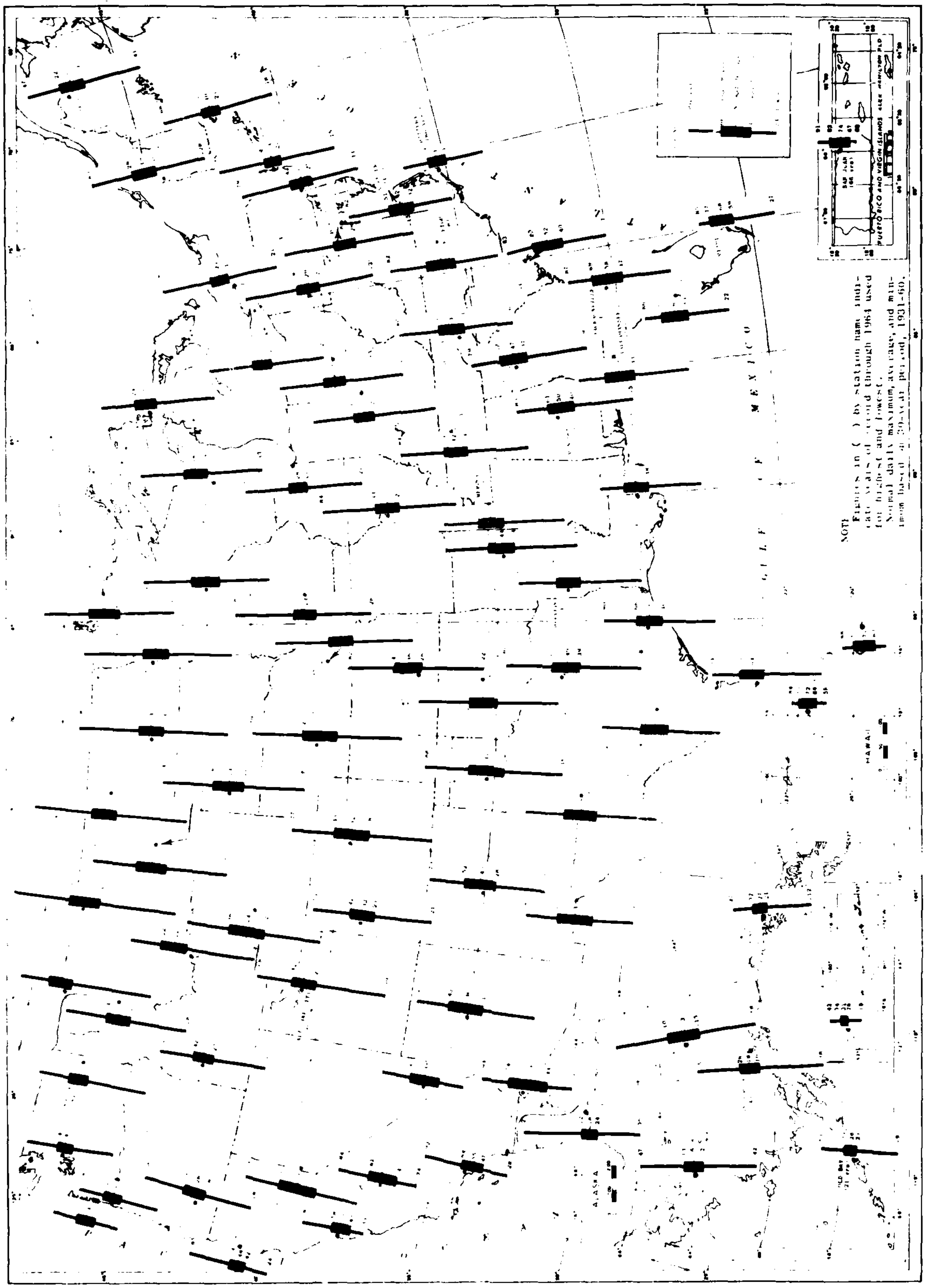

Figure 3-2. NORMAL DAILY MAXIMUM, AVERAGE, MINIMUM, AND EXTREME TEMPERATURES (°F), FEBRUARY

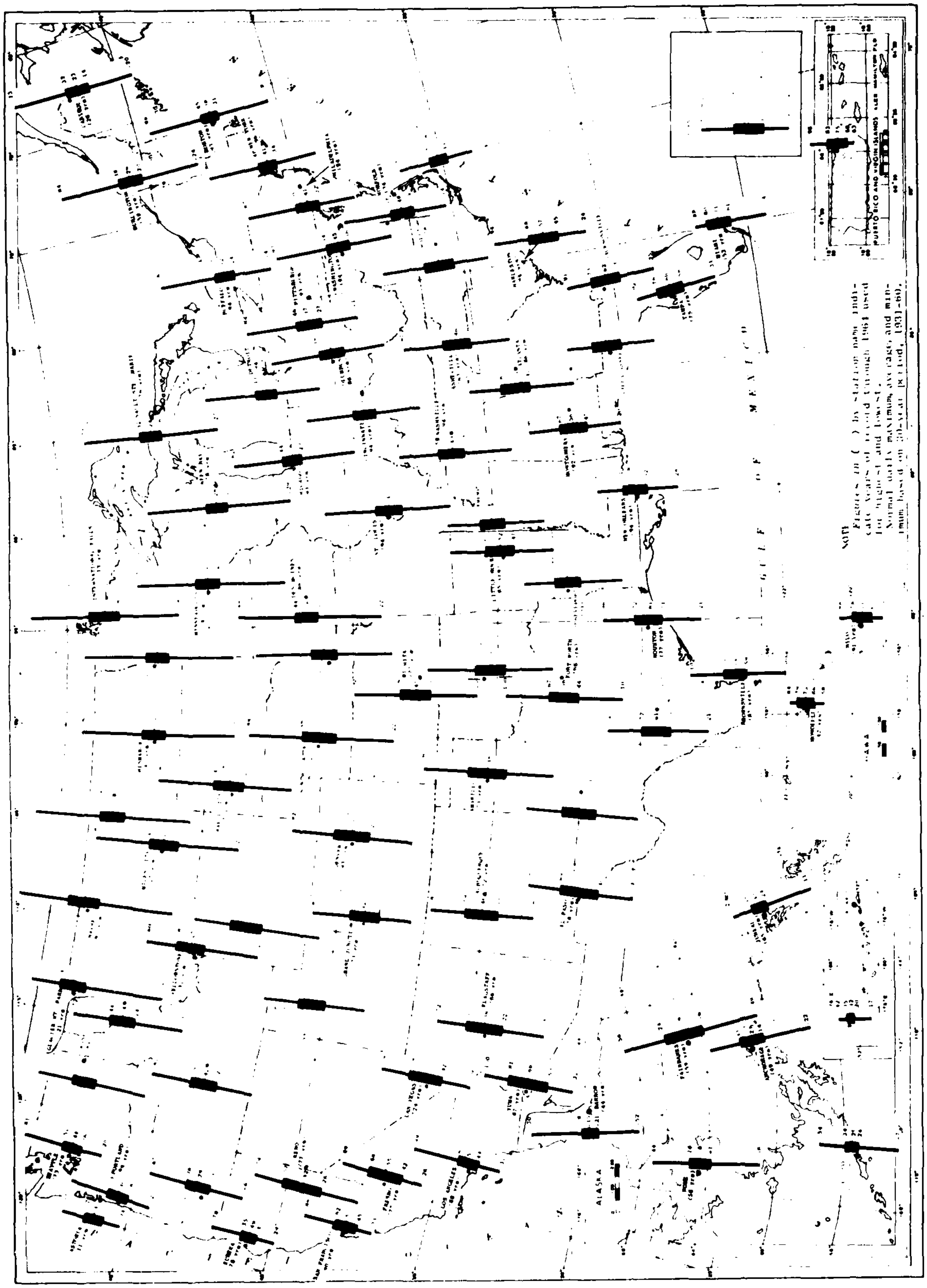

Figure 3-3. NORMAL DAILY MAXIMUM, AVERAGE, MINIMUM, AND EXTREME TEMPERATURES (^{o}F), MARCH

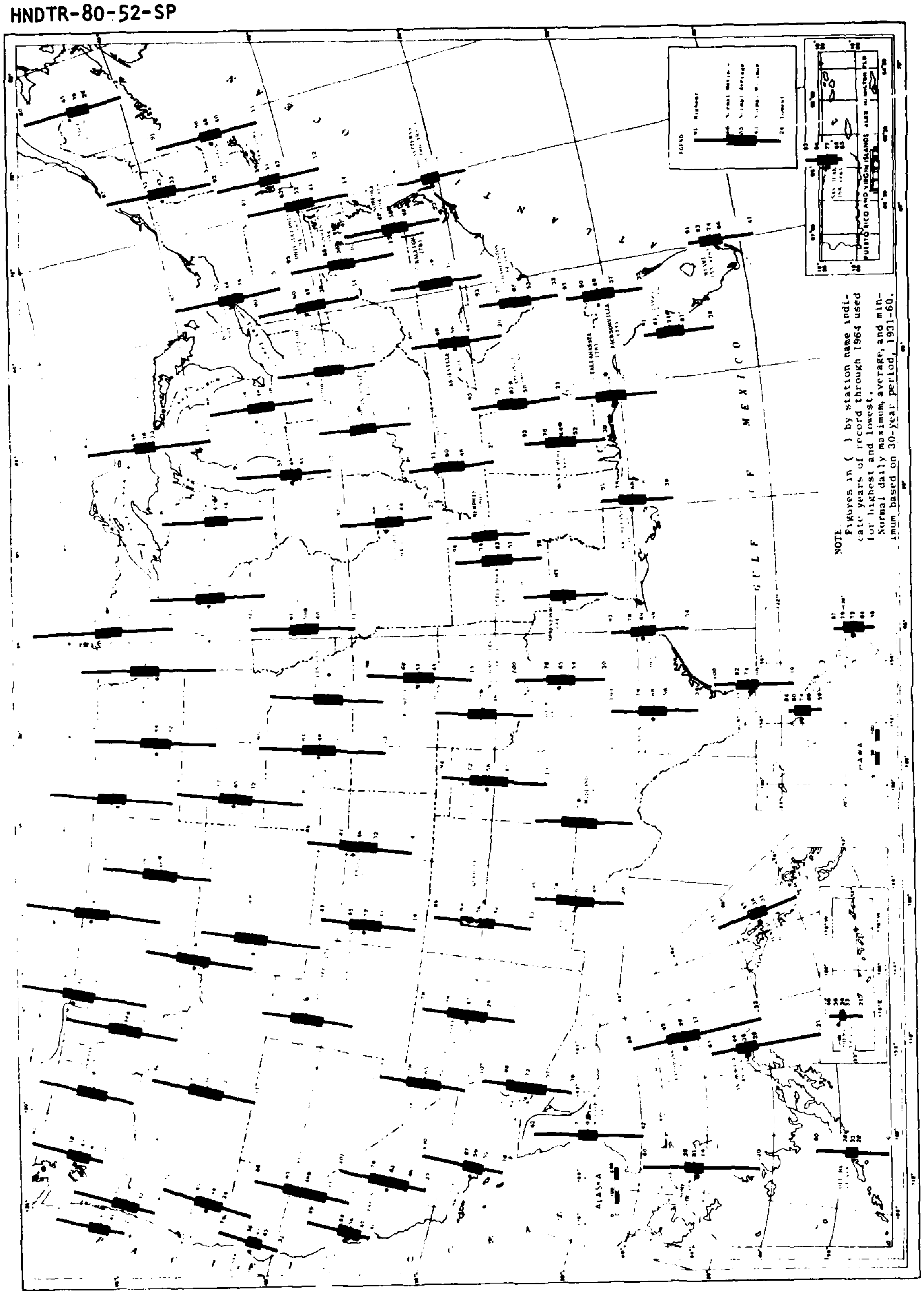

Figure 3-4. NORMAL DAILY MAXIMUM, AVERAGE, MINIMUM, AND EXTREME TEMPERATURES (°F), APRIL

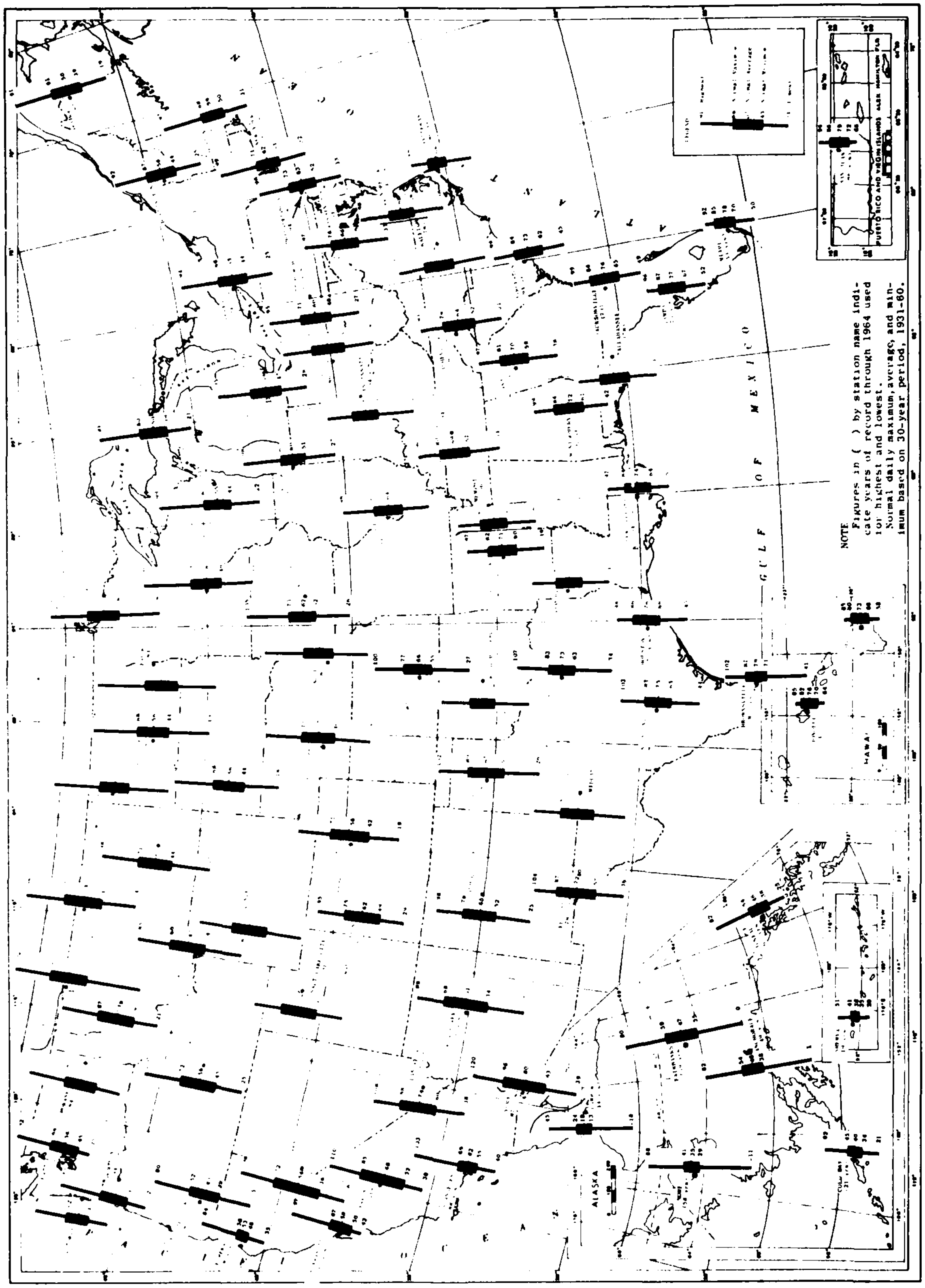

Figure 3-5. NORMAL DAILY MAXIMUM, AVERAGE, MINIMUM, AND EXTREME TEMPERATURES(°F), MAY

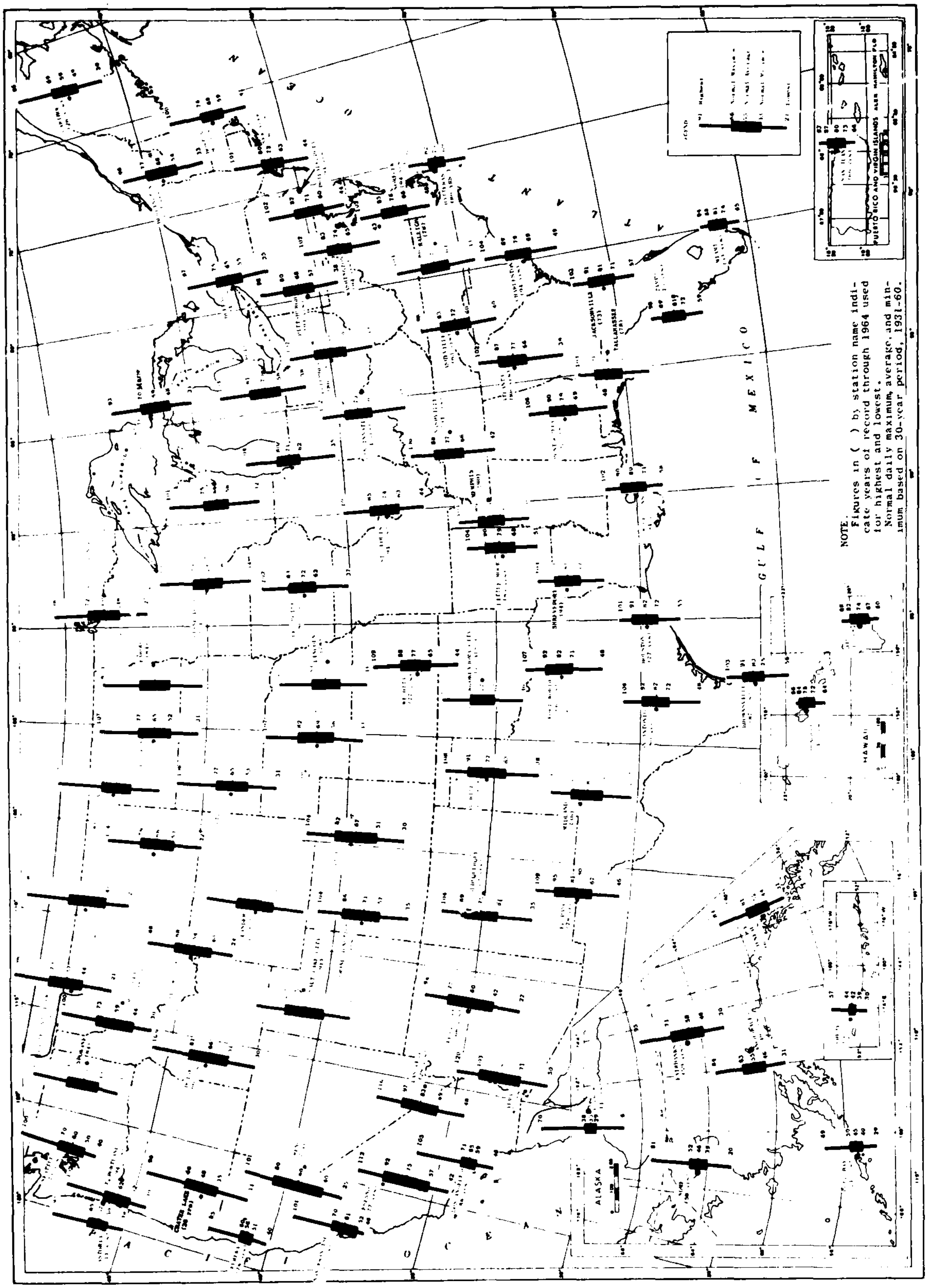

Figure 3-6. NORMAL DAILY MAXIMUM, AVERAGE, MINIMUM, AND EXTREME TEMPERATURES (°F), JUNE

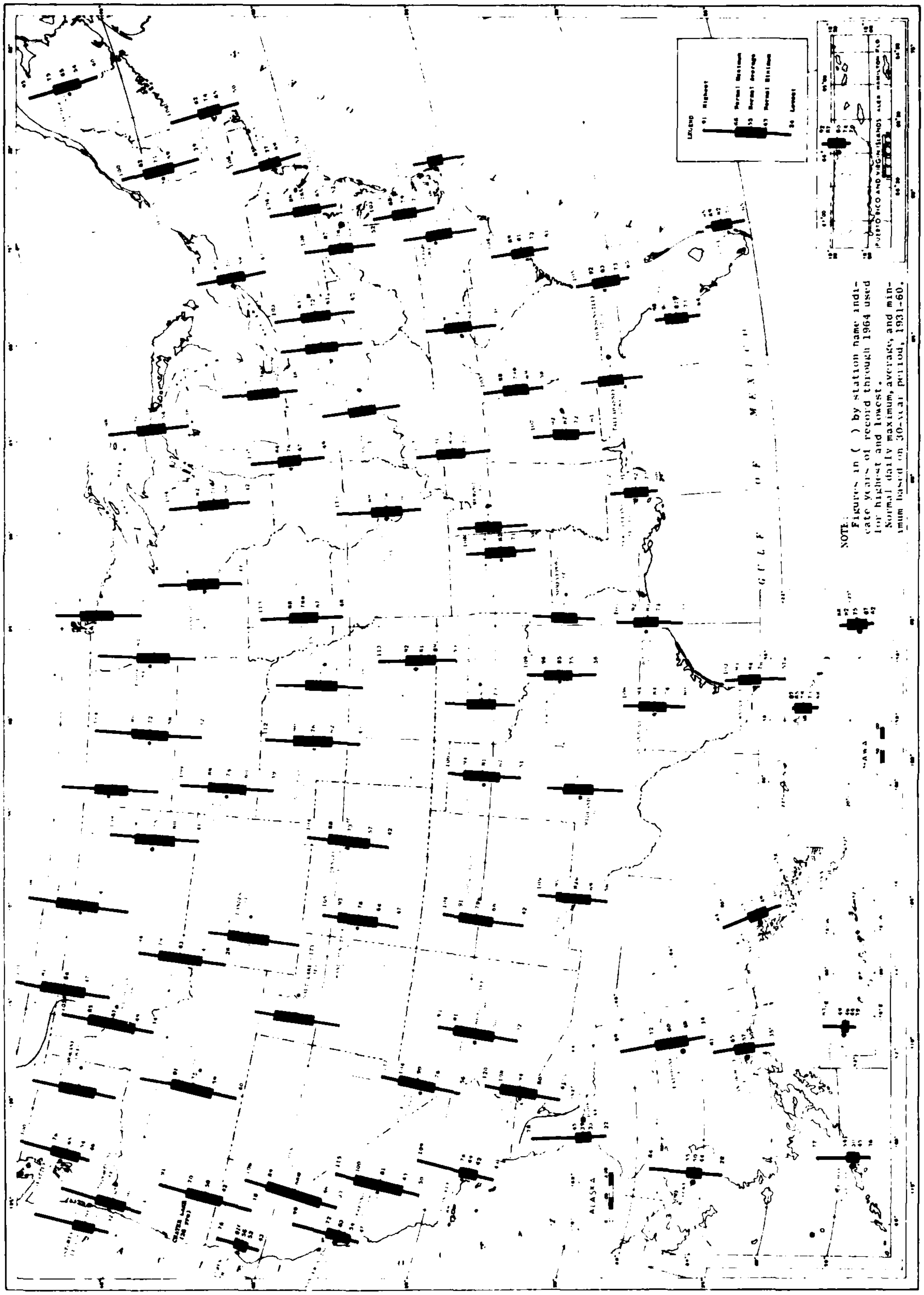

Figure 3-7. NORMAL DAILY MAXIMUM, AVERAGE, MINIMUM, AND EXTREME TEMPERATURES (°F), JULY

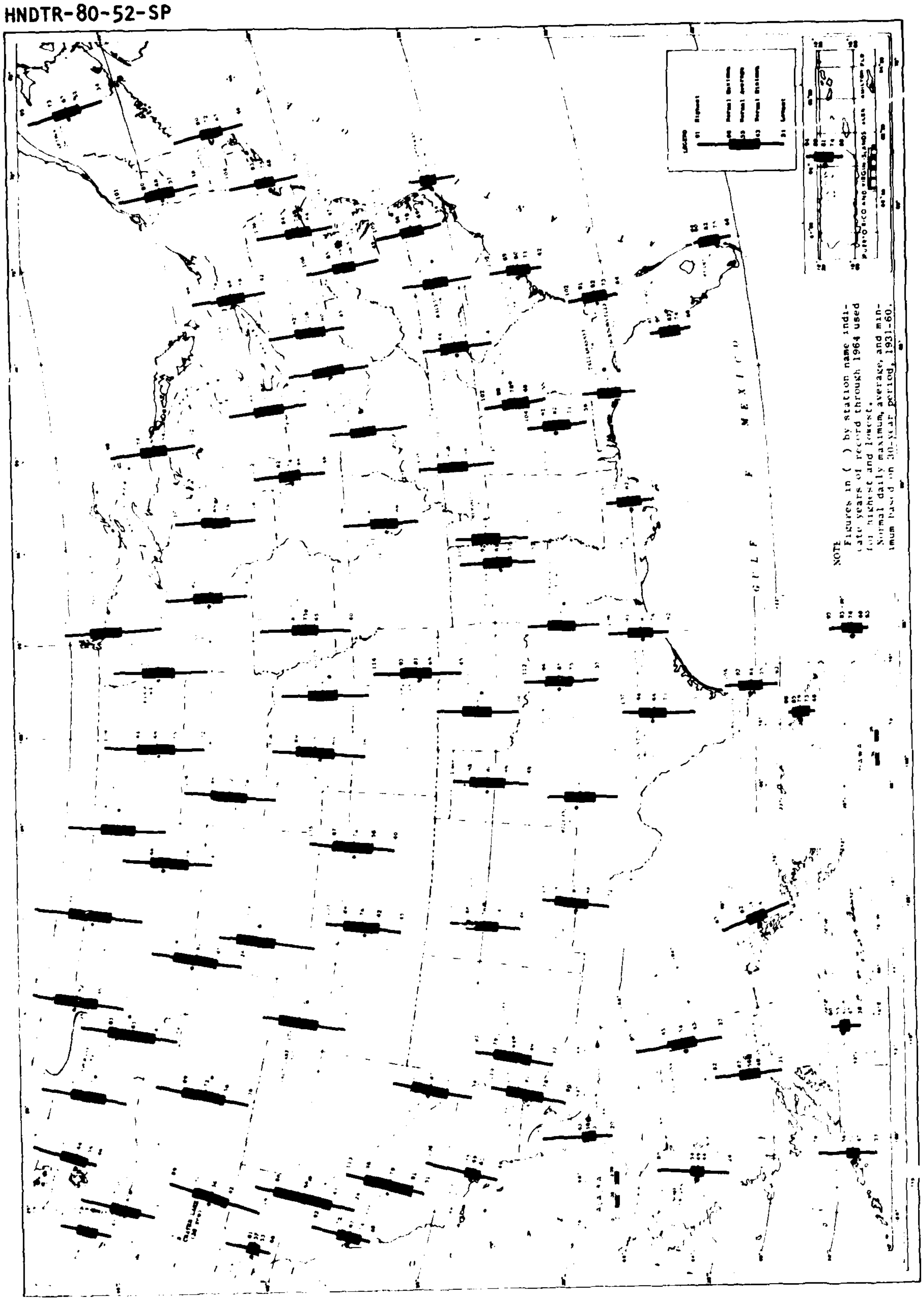

Figure 3-8. NORMAL DAILY MAXIMUM, AVERAGE, MINIMUM, AND EXTREME TEMPERATURES (^{o}F), AUGUST

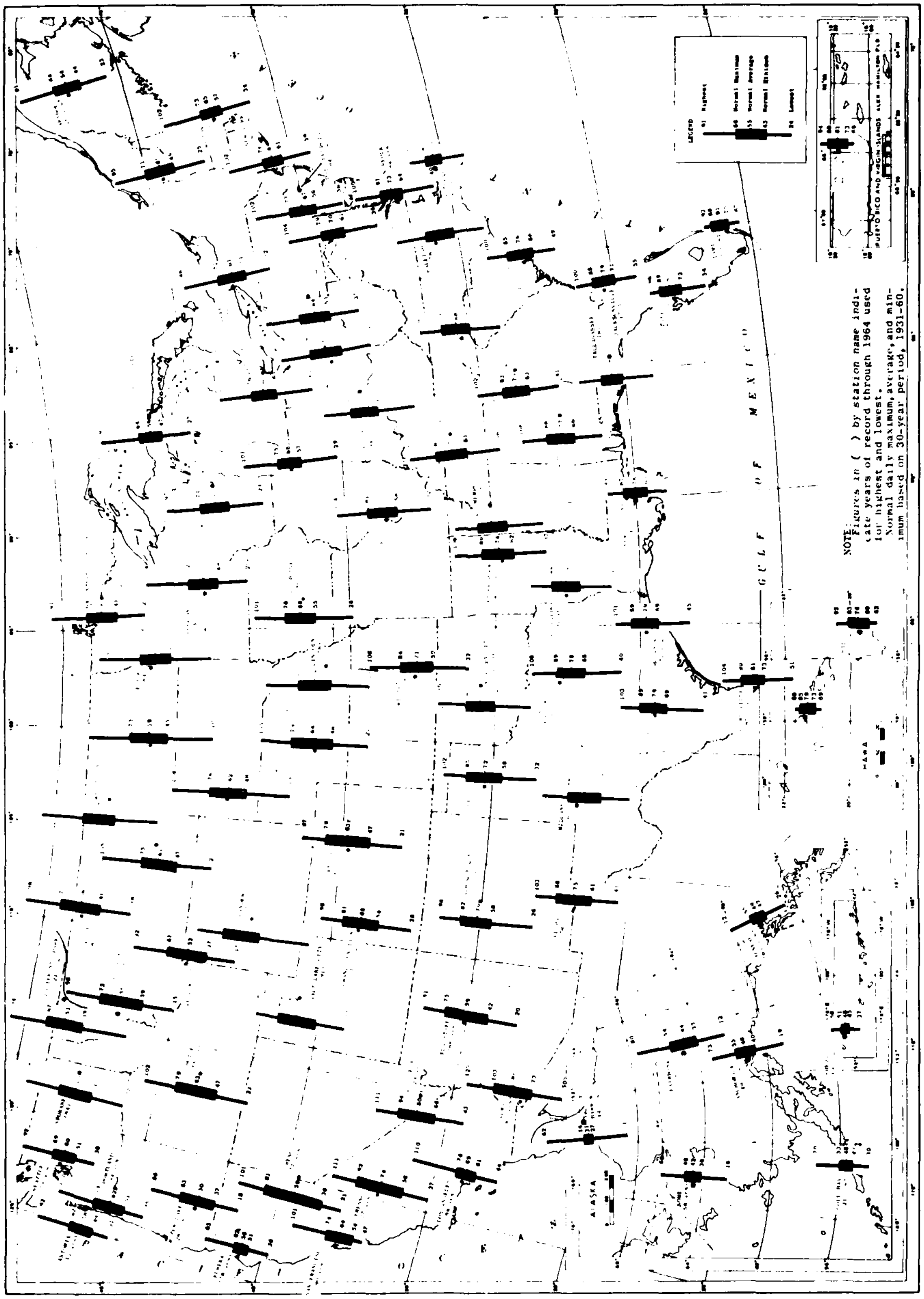

Figure 3-9. NORMAL DAILY MAXIMUM, AVERAGE, MINIMUM, AND EXTREME TEMPERATURES (°F), SEPTEMBER

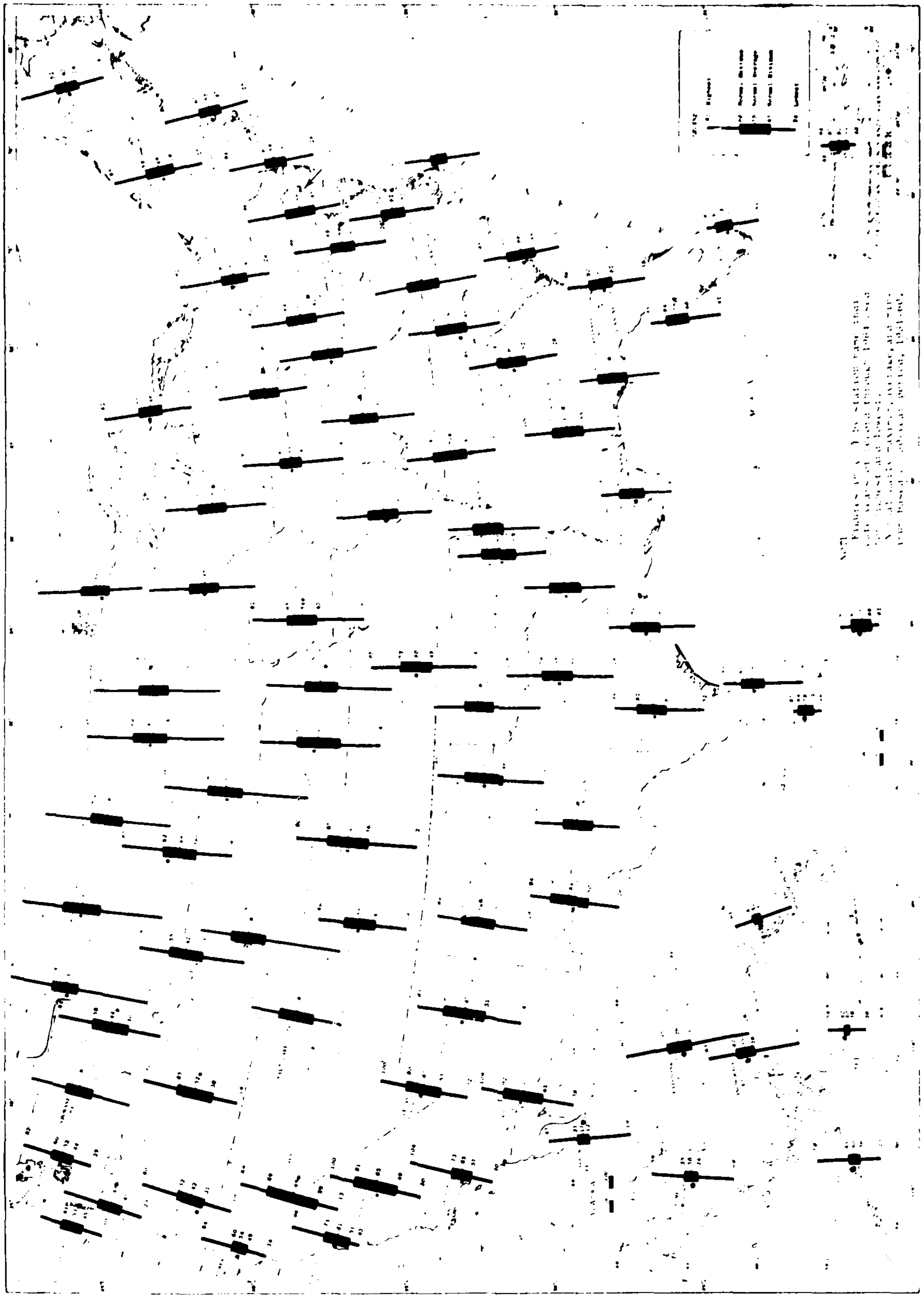

Figure 3-10. NORMAL DAILY MAXIMUM, AVERAGE, MINIMUM, AND EXTREME TEMPERATURES (°F), OCTOBER

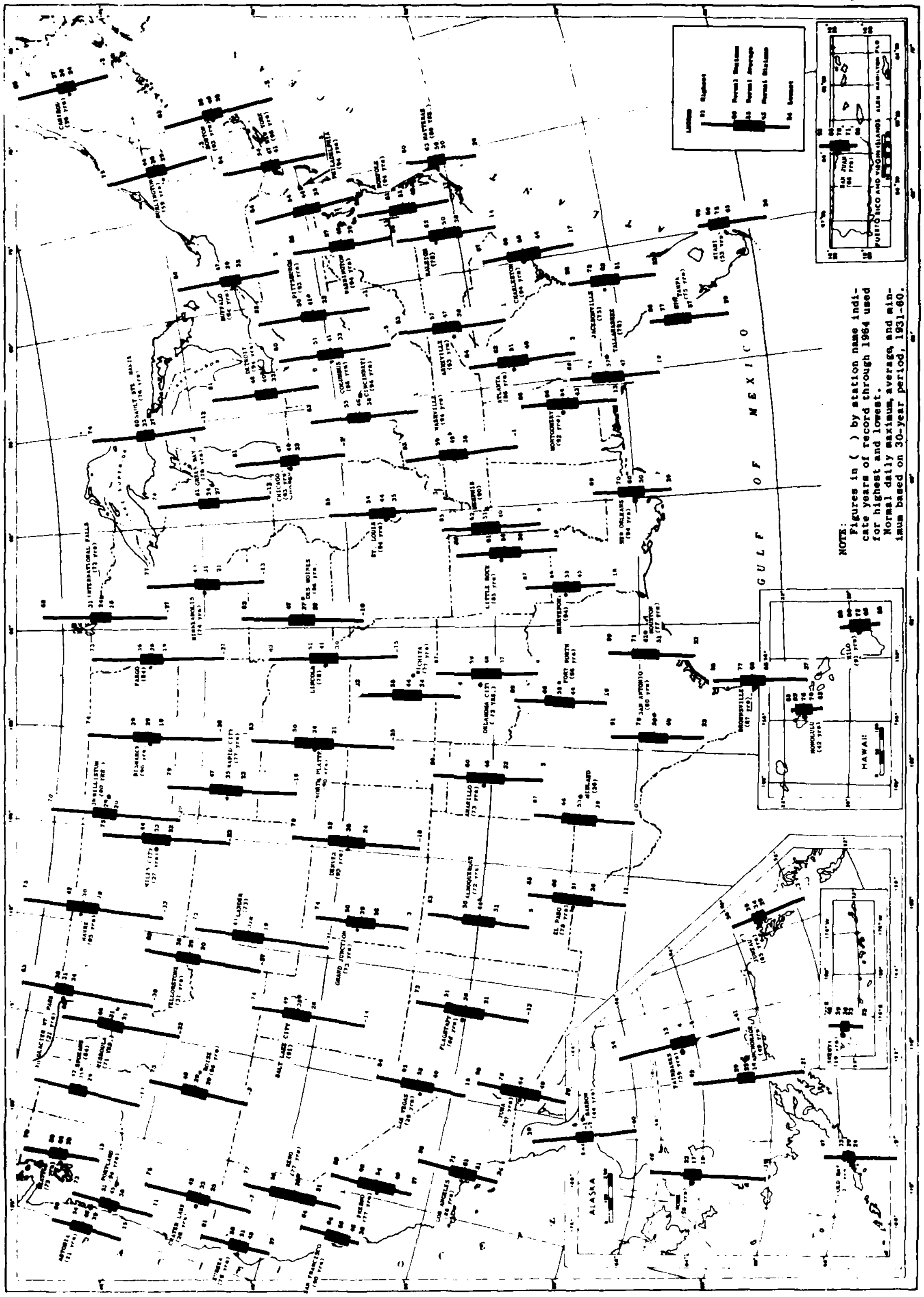

Figure 3-11. NORMAL DAILY MAXIMUM, AVERAGE, MINIMUM, AND EXTREME TEMPERATURES (°F), NOVEMBER

AD-A144 651 EAST COAST REGIONAL PETROLEUM RESERVE (RPR) VOLUME 3 POTENTIAL STORAGE SI..(U) ARMY ENGINEER DIV HUNTSVILLE AL R E SHANNON ET AL. 30 SEP 80 HNDTR-80-45-SP-VOL-3

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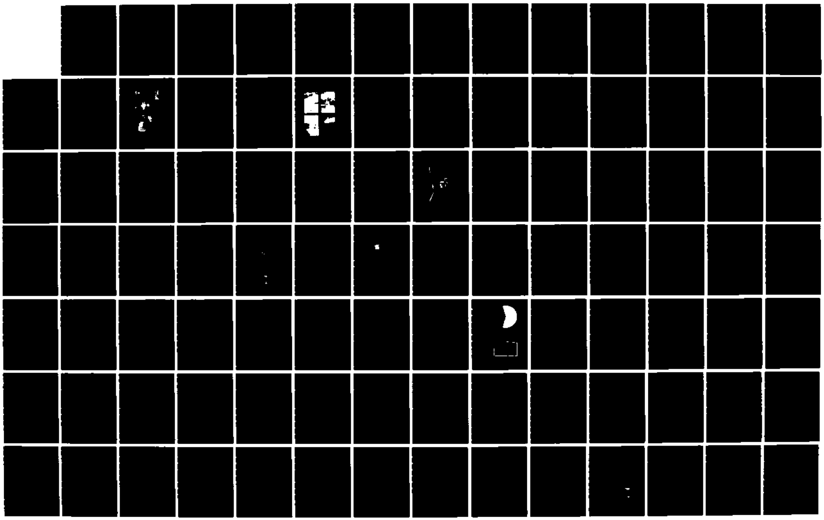
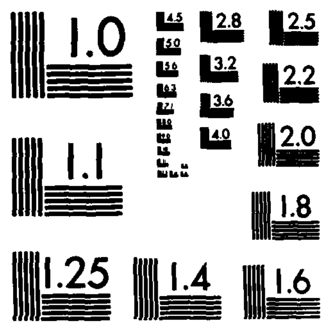




MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

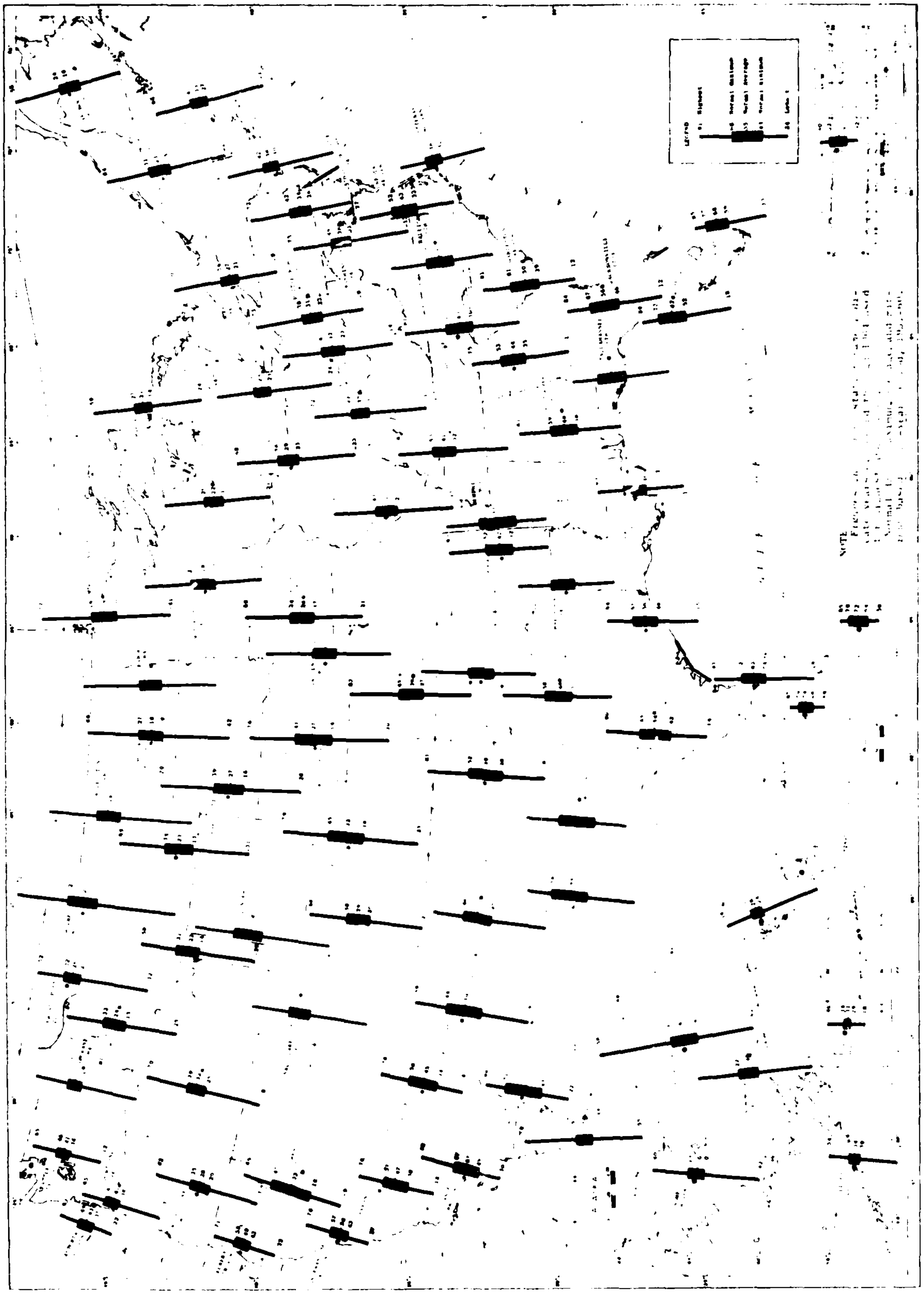
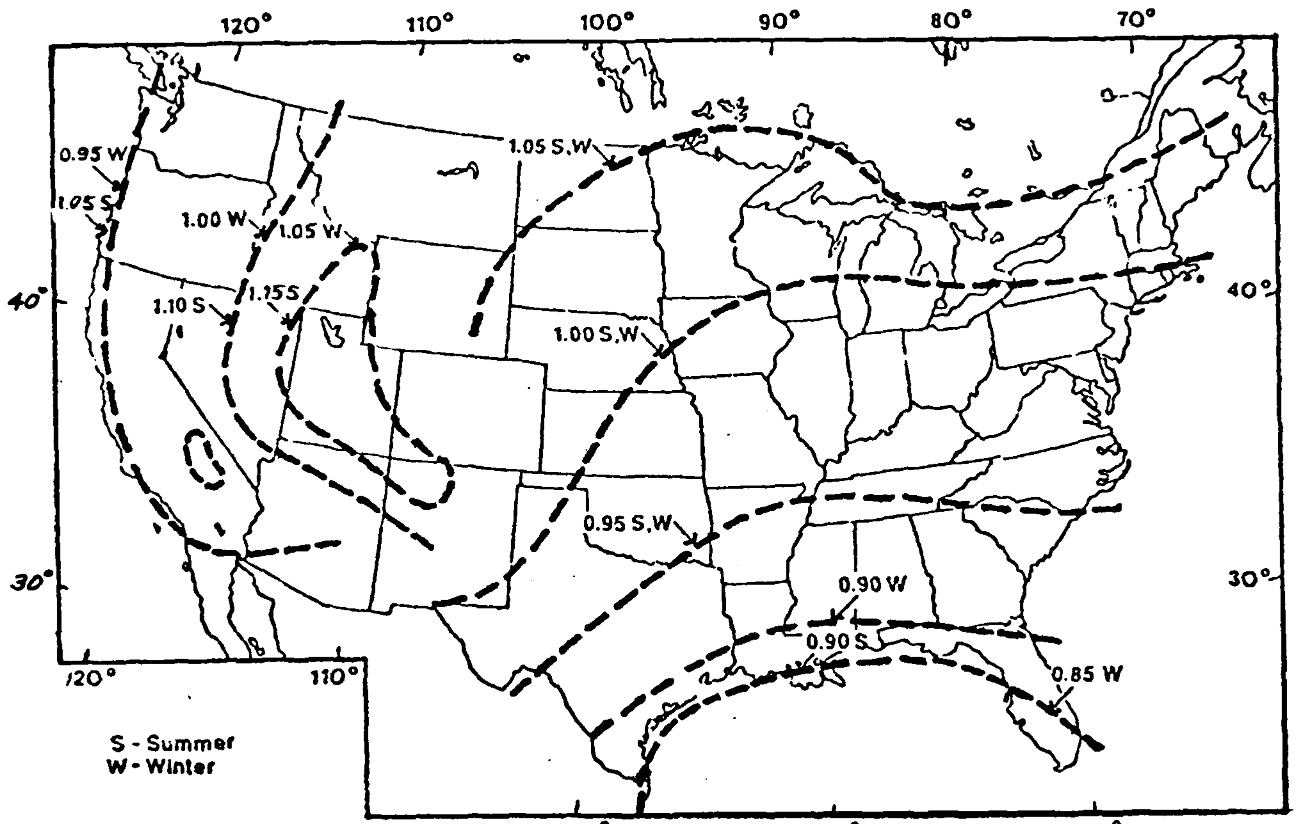


Figure 3-12. NORMAL DAILY MAXIMUM, AVERAGE, MINIMUM, AND EXTREME TEMPERATURES (OF), DECEMBER



Source: [3]ASHRAE Handbook 1977

Figure 3-13. SUMMER AND WINTER CLEARNESS NUMBERS.

Table 3-9. SNOW AND WIND DATA

Location	Mean Monthly Snow (inches)	Snow Load (psg)	Max. Month Wind Speed (mph)	Wind Direction	Month
Portland, Maine	20	14	76	NE	March
New York, New York	10	7	99	N	Sept.
Norfolk, Virginia	6	4	80	W	June
Jacksonville, Florida	0	0	76	SE	Sept.

Source: Climatic Atlas of the U.S.A., U.S. Department of Commerce

Note: Snow Weight = 8 lbs/ft^3

Therefore 1" of snow fall = 0.7 lbs/ft^2

CHAPTER 4
STORAGE CONCEPT DEFINITION

The storage containers and concepts used as a basis for the study were considered to be those closest to the current state-of-the-art for long-term fuel oil storage vessels.

Long-term storage of fuel oil for rapid recovery requires that the storage container and methods must meet the following criteria:

- accessible for fuel oil recovery and equipment maintenance
- container resistance to deterioration by erosion, corrosion, or chemical attack
- container is inert to chemical reaction with the product being stored
- extremely low leakage of product by seepage, evaporation, or leakage
- structural containment of product, hydraulic pressure and wind, snow and dead loads
- capability to maintain or elevate product temperature above 80°F to allow recovery.

In this section, basic descriptions will be provided of storage containers and ancillary equipment which might be considered for heating by solar energy.

4.1 CONTAINERS

Heavy crude oil and No. 6 residual oil are commonly stored in one of three basic types of containers, generally characterized by the location of the container. Storage vessels are generally located as follows:

- aboveground steel tanks
- belowground concrete tanks
- mines

Each of these will be discussed in some detail, particularly in regard to their compatibility with the use of solar energy as a means of maintaining the product temperature at recovery level.

a. Aboveground Storage

Aboveground oil storage tanks are the most common method used for storing fuel oil. These tanks are usually welded steel cylindrical tanks with either a fixed conical roof or a floating roof. Because of the low volatility of residual oils, fixed-roof tanks are commonly used to store these products. Aboveground tanks can be easily constructed with common

steel erection techniques and are easily accessible for maintenance, repair or emptying. The steel is basically inert to chemical reaction with the product, but must be properly treated on the exterior to protect against corrosion. Aboveground tanks can be easily insulated with sprayed-on foam insulation or fiberglass insulation contained in a water-resistant jacket, a necessity if solar heating is to be used. Product loss by evaporation is controlled by proper roof and vent design. The structural design of these tanks is straight forward. Several large tank constructors have designed standard size tanks and have the capability to design vessels of 1,250,000 barrels. Conventional petroleum industry methods are available to heat the product by submersed coils in the tank bottom, or hung from the roof, or by constant pumping of the product through heat exchangers. Aboveground tanks located in tank farms must be separated for fire protection requiring large land surface areas.

Aboveground steel tanks are erected onsite by the screw method shown in Figure 4-1 or by partial pre-assembly using the roll method shown in Figure 4-2. Leaks in the aboveground tank walls are readily apparent and accessible for repair. Aboveground tanks appear to offer the greatest potential for solar heating because of their suitability for passive heating and overall accessibility.

b. Belowground Storage

Large underground storage tanks have been used in recent years in the U.S., Europe, and the Middle East for storing crude oil. Belowground storage containers are typically reinforced concrete constructed on an excavated site or on grade and backfilled and covered with earth. Various underground tank designs are shown in Figure 4-3. Due to its inherent inaccessibility, the underground tank requires special treatment of piping connections, location of mechanical equipment and sealing. The belowground tank has the advantage of lower evaporation losses in addition to reduced flammability risk, and land area requirements. The below grade tank could also provide thermal advantages if the product is stored at a temperature near the annual average air temperature. Leaks in the belowground storage container are not visible and are inaccessible and thereby difficult to repair without draining the tank. Also, any product that leaked below grade would be lost and could cause contamination of the groundwater supply. Passive solar heating cannot be readily accommodated by the underground tanks.

c. Mine Storage

In recent years, mines have been used in Sweden and Germany to store heated residual oil for power plants. The mines are characterized by a large underground cavern or tunnels in the underlaying rock with connecting tunnels and shafts. There are two general types of mine storage, solution caverns and excavated mines. The storage container is usually located in a formation subsurface rock or mineral deposit often below the water table. Solution caverns are large near spherical openings, often a single cavern, formed in deposits of water-soluble salts either

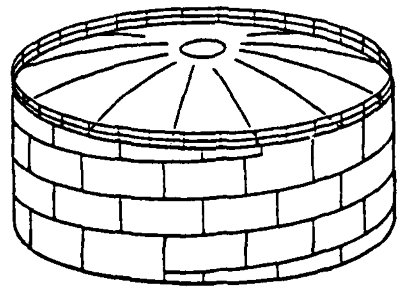


Figure 4-1. ABOVEGROUND TANK SCREW METHOD CONSTRUCTION

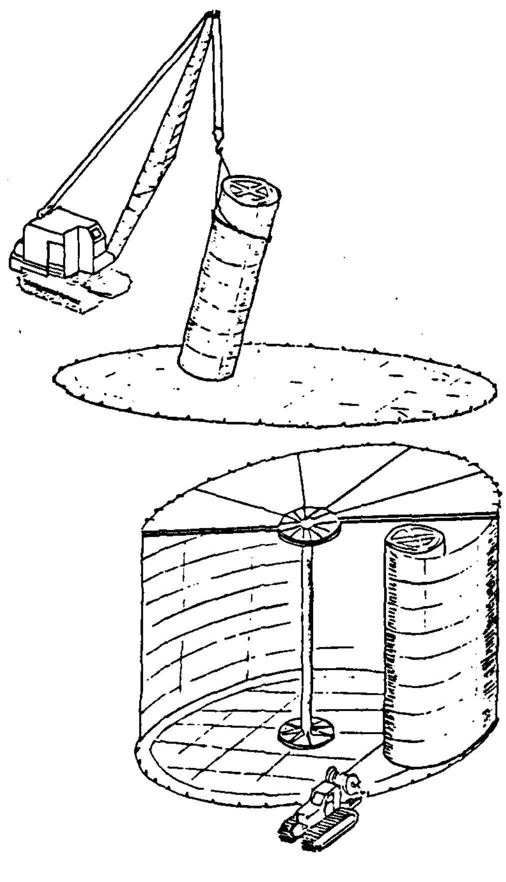


Figure 4-2. ABOVEGROUND TANK ROLL METHOD CONSTRUCTION

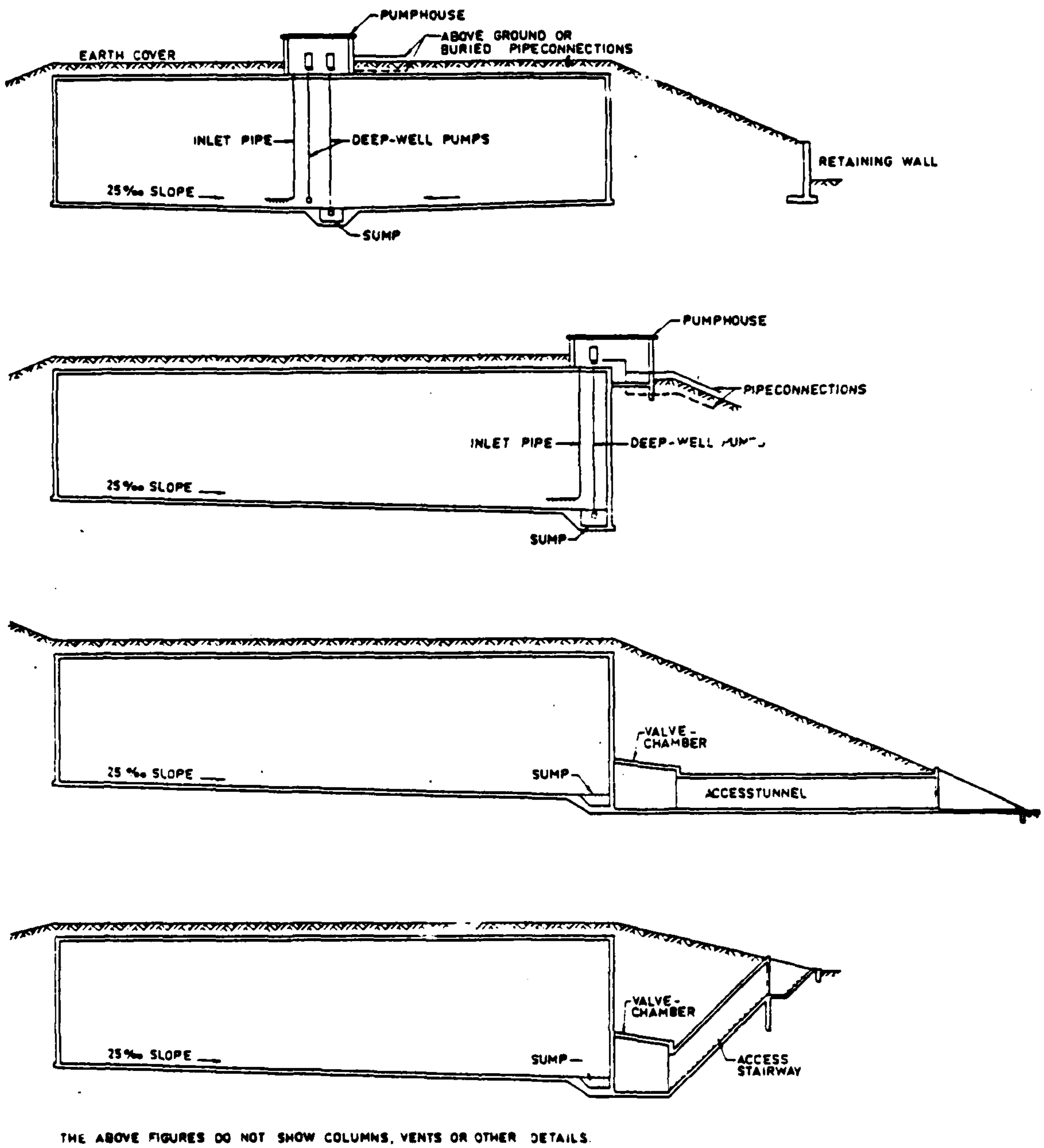


Figure 4-3. BELOWGROUND TANKS

naturally or man-made by pumping in fresh water and pumping out a saturated salt solution. Solution caverns were not considered in this study.

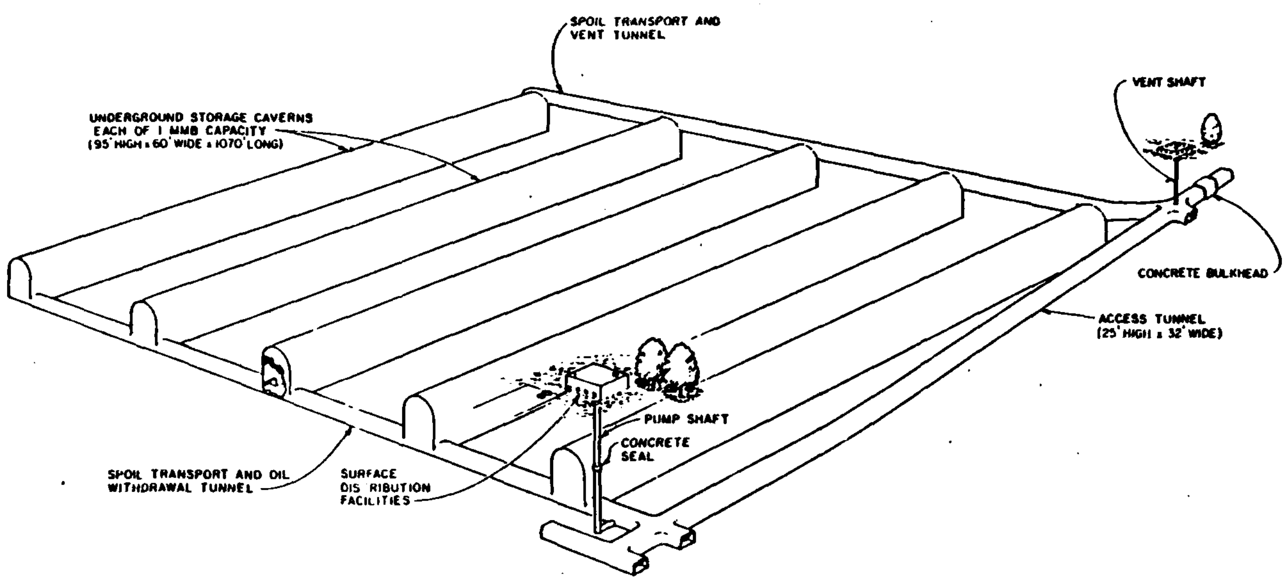
Excavated mines are man-made tunnels, usually long, horizontal and connected by shafts and other connecting horizontal tunnels. Mines are excavated using conventional mining techniques in solid rock. Excavated mines are characterized as either wet or dry depending on the rate of water seepage into the cavern. The mines are maintained at a slight negative pressure by slowly pumping seepage water out of the mine (Figure 4-4).

Mines have a potentially lower construction cost than above- or below-ground tanks particularly if an existing mine or cavern can be used as is. Mines also have a low flammability risk. The primary advantage of mine storage is that little surface land is used. The inaccessibility of mines makes the leak indication difficult, repair impossible, and also, any product loss from leakage permanent. The mechanical equipment used for mined storage must be extremely reliable due to its inaccessibility for repair and also be particularly resistant to corrosion from minerals present in the seepage water. An excavated mine is shown in Figure 4-4. Mined storage is suitable only for active solar systems or heat pumps. Because of the uncertainty about geological conditions, an accurate calculation of heat loss, and hence system size, can be a determining factor in selecting a solar system design.

4.2 HEAT EXCHANGER

The heat exchanger provides energy to the product to make up for that loss from the tank envelope. The heat exchanger is a coil of pipe through which hot steam, oil or water is pumped from a boiler system. The coil is located either horizontally in the bottom of the tank or is dropped vertically through a manhole into the product. Two horizontal heating systems are shown in Figures 4-5 and 4-6 for a 1,250,000-barrel tank. The heat exchanger coils often have a finned surface to improve the heat transfer to the product. The coils are most commonly made of steel through which steam is circulated. In order to maintain a constant product temperature, the conventional oil tank heating system must transfer heat at a rate equal to its heat losses. Currently, many oil storage tanks are only temporary storage and are often uninsulated, thereby imposing large heat loads on the heating system.

A horizontal heat exchanger located at the bottom of the tank heats the cool product which becomes less dense than the cooler fluid in the layers above. The resulting instability induces fluid motion that tends toward uniform temperatures throughout the product. A bottom heat exchanger, however, is located where it is not readily accessible. If a leak occurs in the heat exchanger inside the tank, the heat system fluid leaks into the product. This can cause sludge formation or other operational difficulties. The storage tank must be emptied of the product to repair a leaking heat exchanger, thus making it necessary to transfer the product during storage, which may be undesirable in a long-term storage reservoir.



Source: Strategic Petroleum Reserve, Phase 5, Underground Mined Storage, Flexability Analysis, U.S. Federal Energy Administration, September 1976, Plate 2, Appendex

Figure 4-4. EXCAVATED MINE STORAGE FACILITY LAYOUT

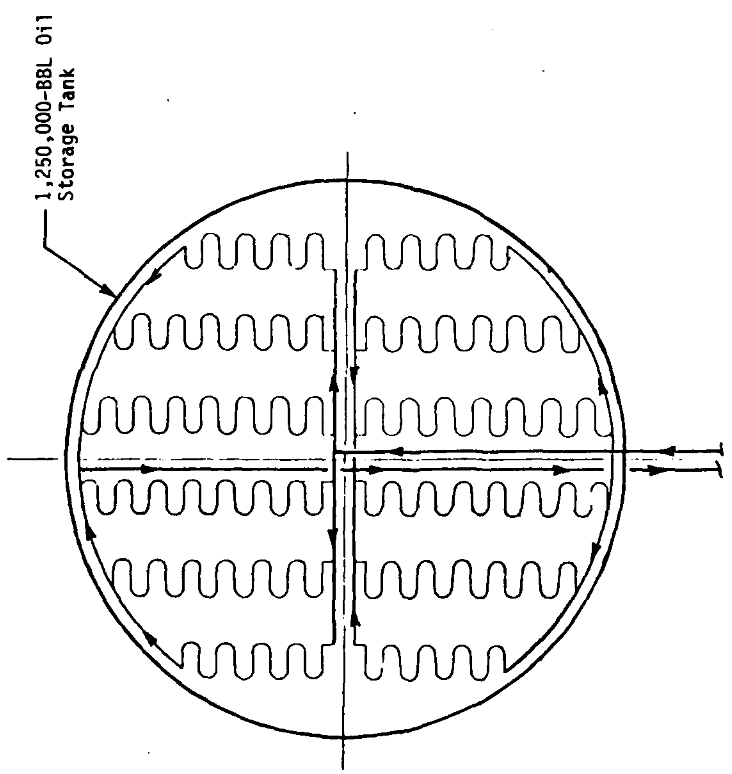


Figure 4-5. TANK HEATING SYSTEM/OIL HEATING MEDIA PIPING

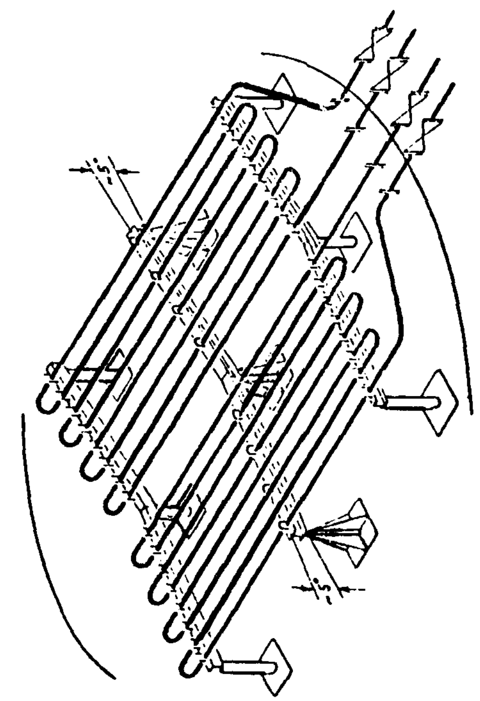


Figure 4-6. HORIZONTAL TANK HEATING COILS

The vertical tank heat exchangers have pipes or coils which are dropped down to the bottom through a manhole in the roof. A vertical tank heating coil is shown in Figure 4-7. These heaters also heat the product near the bottom of the tank. If a leak occurs in the tank coil the heat exchanger can easily be removed and se· iced or replaced. Heat transfer fluid leaks can be controlled and isolated easily. The vertical tank heaters are located throughout the roof, heating the product in different parts of the tank. Stirrers are also used to mix the product and distribute the heat.

For long-term storage of a product that requires constant heating, insulation must be used to reduce the tank heat losses, especially if solar is the heating mechanism. With a reduced load and a longer period to heat the product, a capital intensive solar heating system that maintains the product temperature year round becomes more feasible. The solar system heat exchanger would have to tr··sfer heat equal to the annual losses of the tank. On a daily basis, the .iar heat exchanger must able to transfer the energy collected by the array and transfer that eat to the product. The solar collector operates more eff·ciently when collector fluid inlet temperature is lower. It is desirable theref to keep the temperature differences across the heat exchanger as low a possible to keep the collector efficiency high, as shown on Figure · In addition, to keep the collector efficiency high, it is desirable to keep the temperature rise in the collector ($T_{out} - T_{in}$) equal to or less than 10°F.

The heat exchanger must transfer the daily solar energy collected by the collector array with low temperature differences during the daylight hours. The maximum heat transfer rate for this solar heat exchanger occurs at noon in the summer when the ambient air temperature is high and the solar radiation is high. A conventional heat exchanger of the type used currently by the petroleum industry in heating oil in storage tanks can be sized to heat the product with a solar system. The conventional tank heaters have a large heat transfer surface in the product and hea it by natural convection. Only convection oil tank heat exchangers of the types in current use are considered in this study. In a solar system the hot fluid leaving the collector and entering the heat exchanger will be 100-140°F. This is a lower temperature than the 180-210°F steam or water in conventional tank heaters required to achieve high heat transfer rates required in a solar system with lower temperature differences that are desirable for collector efficiency. An efficient design must therefore consider the heat exchanger and collector as a unit.

The solar heat exchanger is also part of the solar collection fluid loop and must be chemically compatible with the collector fluid and other materials used in the collector piping and the collector. If the heat transfer fluid is not a dielectric, galvanic corrosion can occur if dissimilar metals are used in direct contact. The heat exchanger should be made of the same material as the piping (i.e., copper or brass) or it should be isolated from direct contact with the dissimilar metal piping with a dielectric connector.

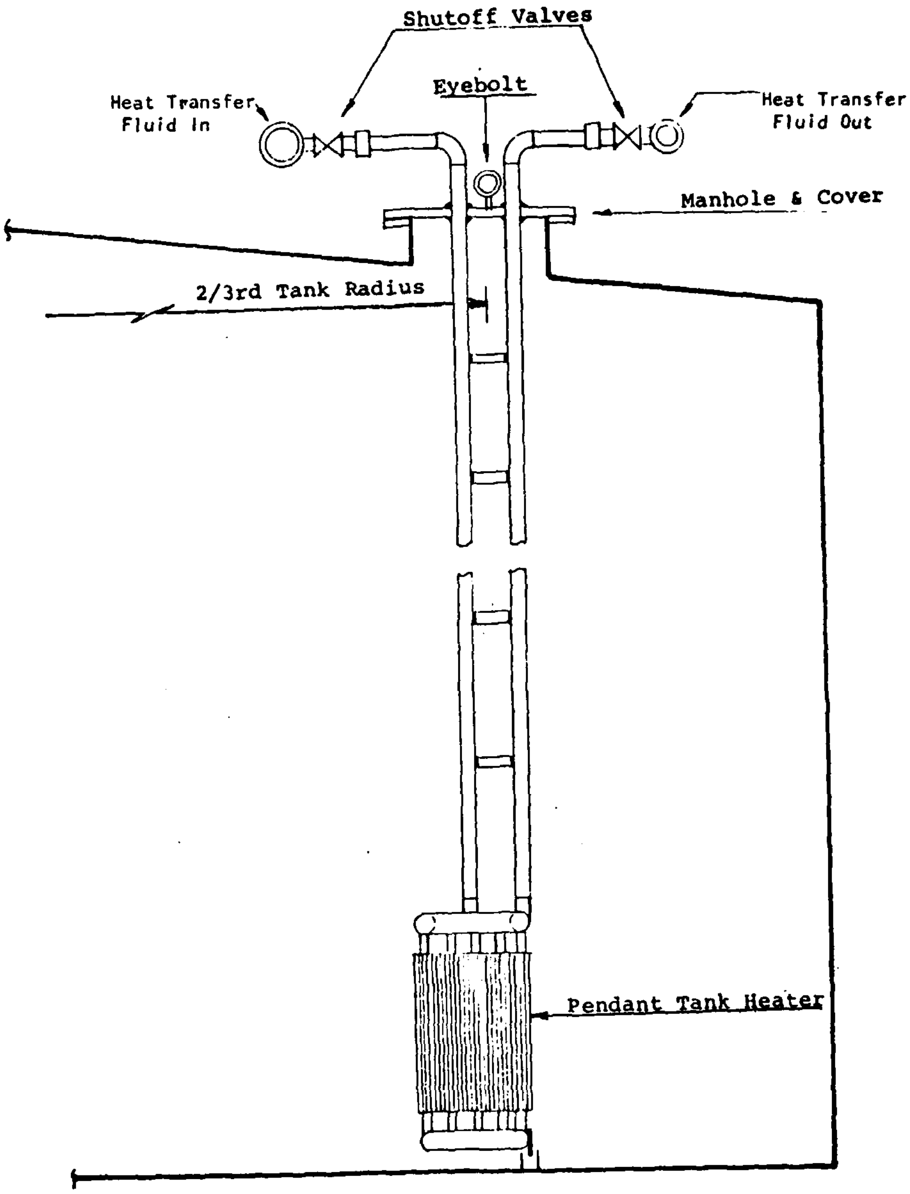


Figure 4-7. VERTICAL TANK HEAT EXCHANGER

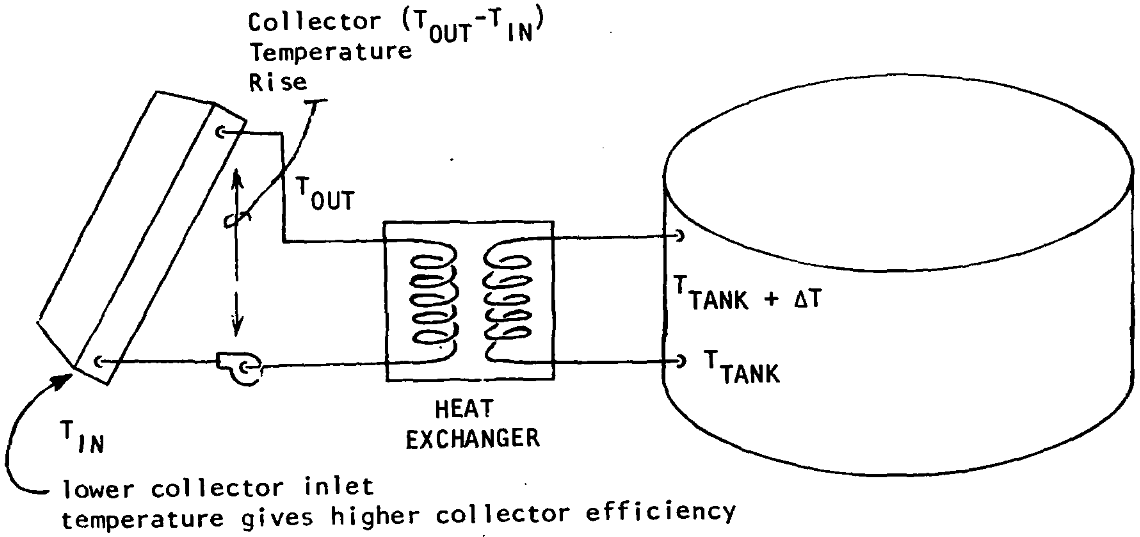


Figure 4-8. TYPICAL HEAT EXCHANGER TEMPERATURES AS DETERMINED BY TANK AND COLLECTOR TEMPERATURES

If the product must be quickly heated up from long-term storage at approximately average ambient air temperature to a temperature that can be easily pumped (80°F), then very large heat transfer rates will be required. Then a heat exchanger area larger than currently used in continuous storage heating systems will be needed. If a heat source other than a boiler plant is used (i.e., heat pump) the temperature of the fluid delivered is generally lower than the 180-120°F of the boiler. The lower temperature differences of the heat pump would require a larger heat transfer area of the heat exchanger to heat the product in the same time as the boiler.

4.3 STIRRERS

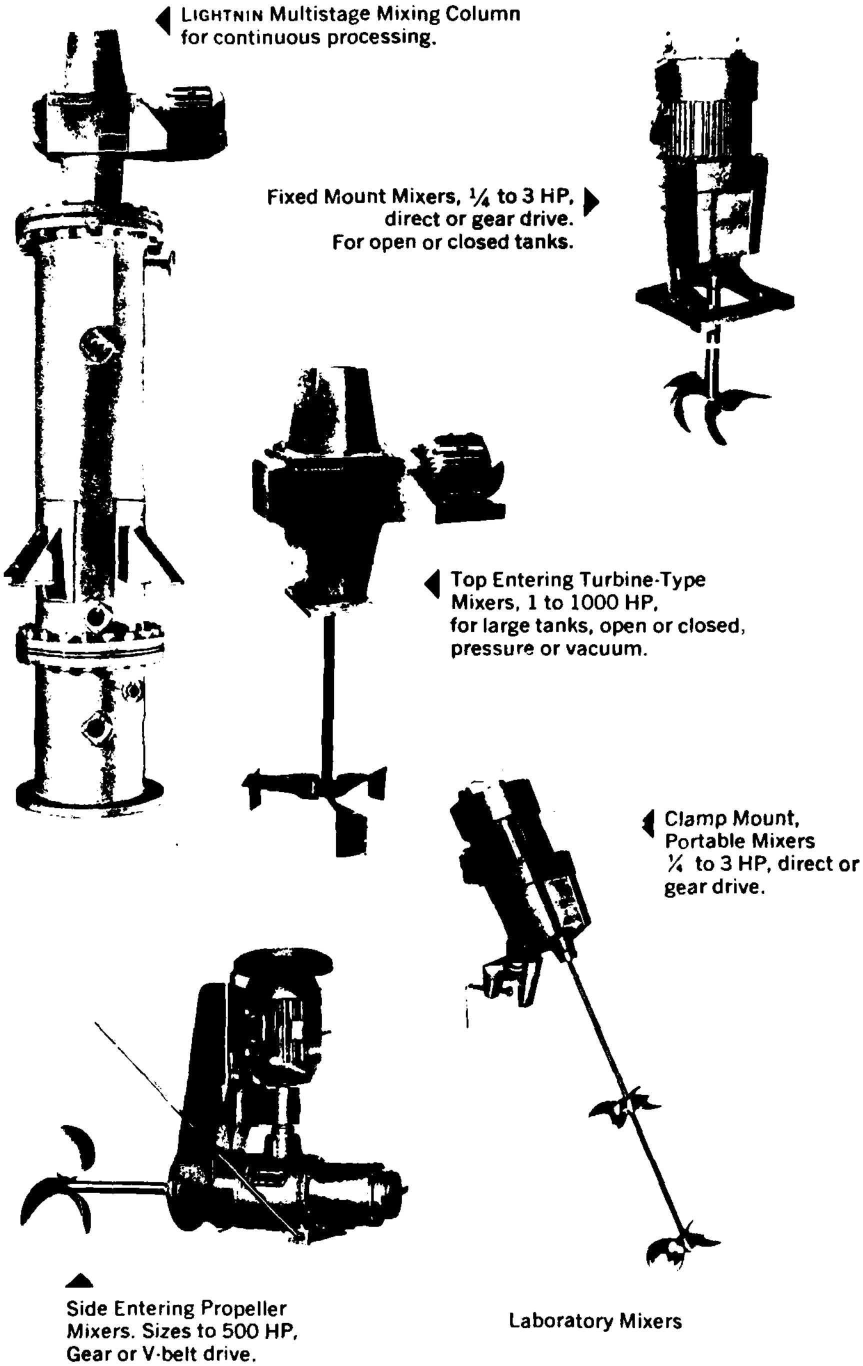
Stirrers are commonly used in large storage tanks to mix the product and to distribute the heat from the heat exchanger throughout the tank. The stirrers are often propeller-type mixers which directly mix the product. The stirrers are run by electric motors which are mounted on the side wall of the tank or on the roof with the shaft passing through the tank wall. Stirrers are readily available up to 75 hp to mix viscous products. With very heavy viscous products, mixing becomes particularly important to move the product by the heat exchanger and to heat the product quickly. Several stirrers used in large storage tanks are shown in Figure 4-9.

4.4 INSULATION

When storage tank products are heated above the ambient air temperature the heat losses from the tank walls, roof, and foundation must be supplied by the heating system. A cost-effective approach to reducing this heating energy requirement is to insulate the tank walls and roof. Existing storage tanks are often insulated particularly if they are storing a high temperature product. Current practice involves using either a mat insulation such as fiberglass or sprayed foam insulation such as polyurethane. Generally, the insulation is applied to an aboveground steel tank in thicknesses from 1-6 inches and covered with a water impermeable weather barrier to protect the insulation from moisture.

Insulation applied to steel tanks should have the following characteristics:

- operating temperature limits should be well above the temperature of the heated product
- light weight so that the insulation weight does not strongly affect the structural design
- high insulating value per cost



Source: Product Literature, Mixing Equipment Co. Inc., Lightnin Mixers, Rochester, N.Y.

Figure 4-9. STORAGE TANK STIRRERS

- insulation should not contain materials that could be corrosive to the steel tank (some insulations can give off a weak acid solution if they become wet.)

- steel tank walls and roof are usually painted with a coating to protect the steel

- long life with little reduction in insulating value

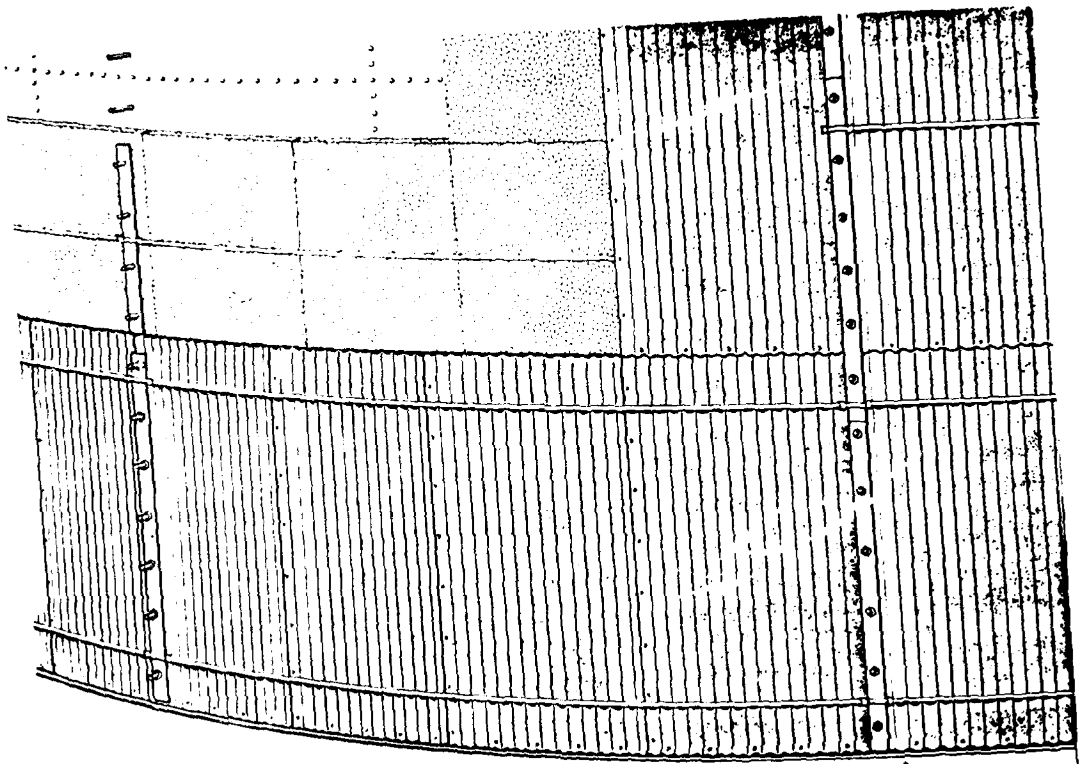
- weather barrier coating should be applied on the exterior of the insulation to keep out moisture

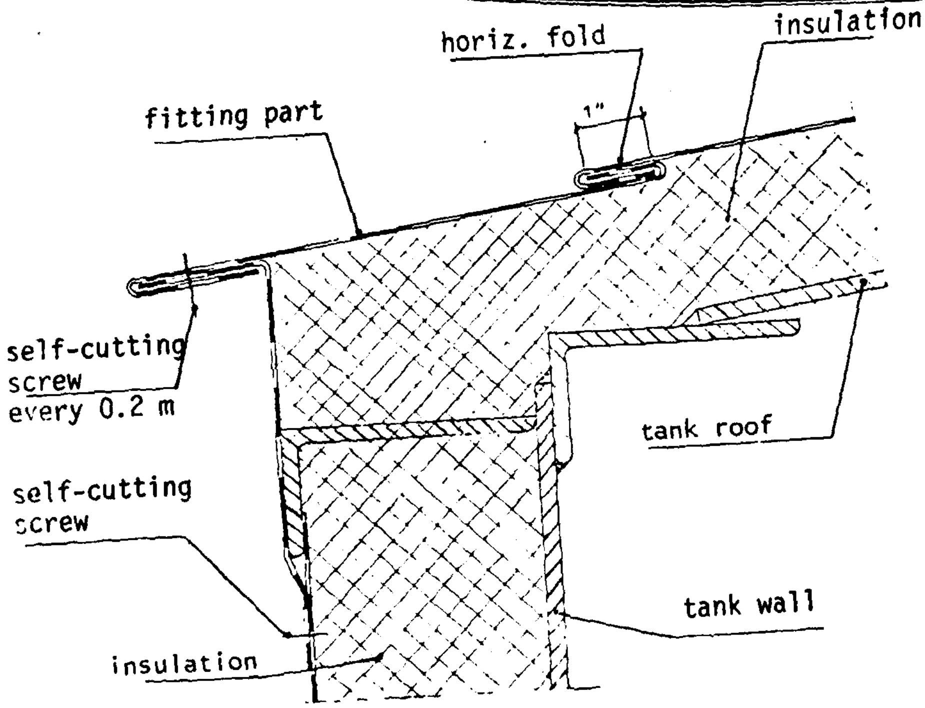
- a supporting framework must be applied to the tank to hold up the insulation or the insulation itself must have enough structural strength to support its own weight

- when storing flammable products, the insulation should be fireproof or appropriately protected from fire hazard.

Matt insulations are usually fiberglass or rock wool batts that are applied between a supporting structure and then covered and held in place with a sheet metal cladding of galvanized steel or aluminum. A typical matt insulation section on a tank is shown in Figure 4-10.

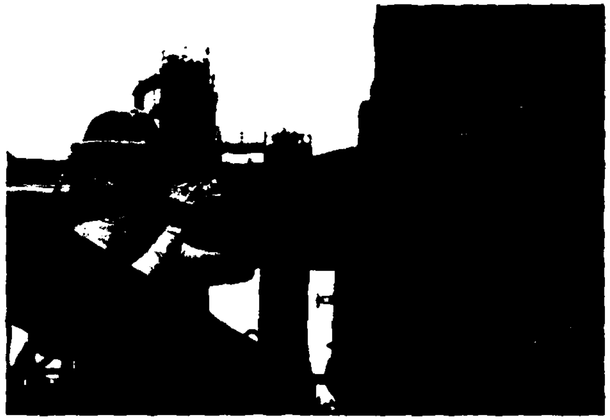
Sprayed-on foam insulations are usually applied over a tank primer in one-half-inch thick layers until the desired total insulation thickness is reached. A sprayed-on elastomeric weather barrier is then applied in two layers of different colors to assure complete coverage. Applications of spray foam insulation are shown in Figure 4-11.





Source: Product Literature

Figure 4-10. MATT-TYPE STORAGE TANK INSULATION



Tank surface is first sand-blasted to ensure good adhesion of the primer.

Primer is applied and allowed to cure thoroughly before urethane spray is applied.

Spray Urethane Foam is applied, in thicknesses up to one inch per pass; additional applications build thickness to meet thermal requirements.

Weather barrier is spray-applied as a protective surface covering.

Figure 4-11. APPLYING SPRAY URETHANE FOAM

CHAPTER 5
CONCEPT FORMULATION

Because the application of solar to large residual oil storage facilities is unprecedented, the study undertook to identify and examine as many design concepts as time and resources permitted. The basic technical and economic characteristics of solar emerged from the few design concepts examined, but the possibilities for identifying optimum approaches were not exhausted.

Three generic classifications of solar energy systems concepts were considered in the present study:

active solar systems - these systems typically employ a flat plate collector to heat a fluid which in turn heats the product. Pumps and other mechanical components are a basic feature of active systems.

passive solar systems - these systems employ a collector which is integrated into the tank structure so that the product is heated directly. These systems are characterized primarily by the absence of pumps to circulate a heat transfer fluid.

heat pumps - these systems employ the vapor compression refrigeration cycle to extract heat from a low cost solar collector or from a waste heat source.

In the following sections, the various system concepts will be described more fully.

5.1 ACTIVE SOLAR SYSTEMS

Figure 5-1 illustrates some of the active system configurations that could be employed for heating residual fuel oil. The letters A, B, and/or M indicate whether the concept can be applied to aboveground tanks, belowground tanks or mined storage systems. The systems in the boxes indicate those that were examined in some detail for cost and technical feasibility.

Active solar systems are comprised of three basic subsystems. These are:

- collector
- transport subsystem
- distribution subsystem

Each of these will be discussed below for application to residual oil storage.

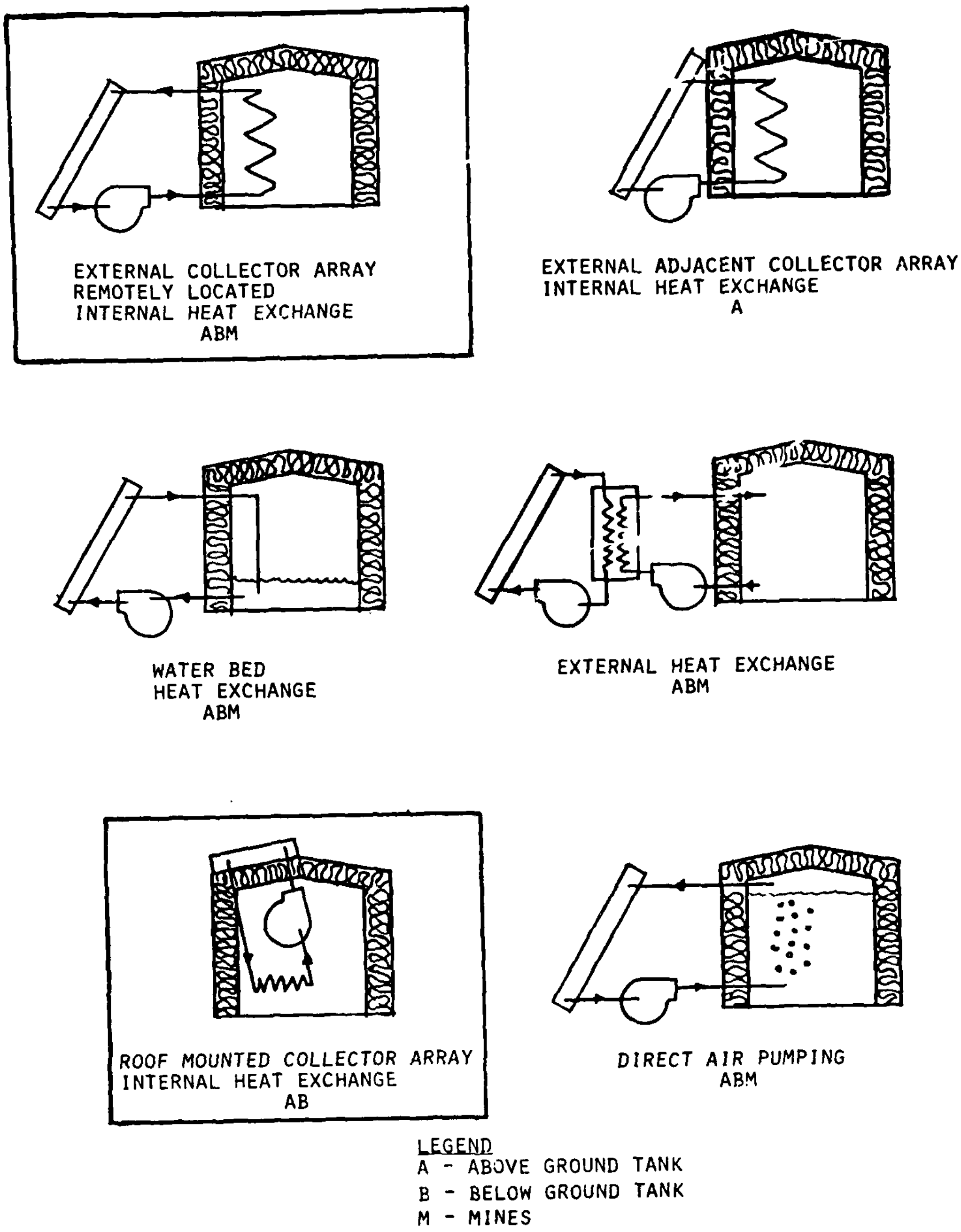
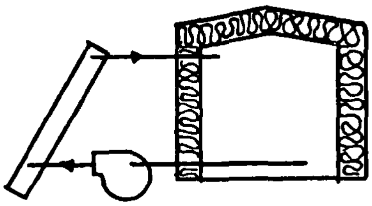
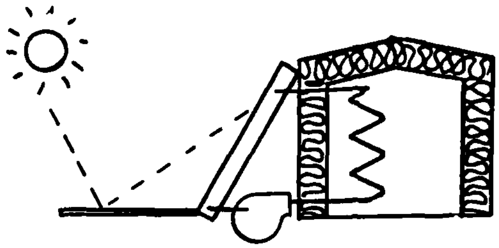


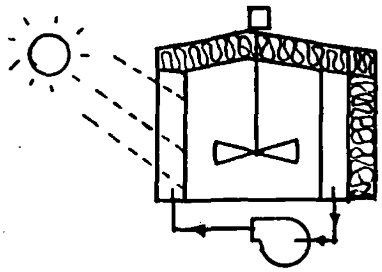
Figure 5-1. ACTIVE SOLAR SYSTEMS



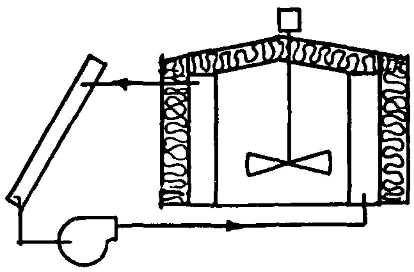
DIRECT PUMP
ABM



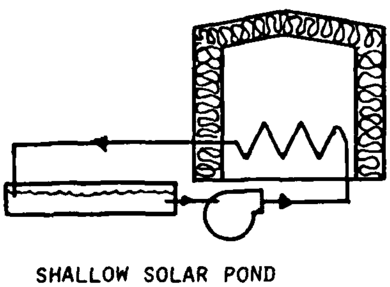
EXTERNAL COLLECTOR
REFLECTOR AUGMENTED
INTERNAL HEAT EXCHANGE
ABM



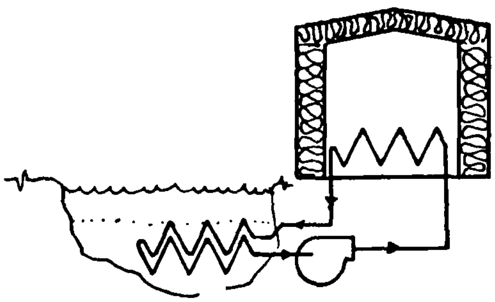
TANK WALL COLLECTOR
TANK WALL HEAT EXCHANGE - STIRRING
A



AIR COLLECTOR
TANK WALL HEAT EXCHANGE - STIRRING
AB



SHALLOW SOLAR POND
INTERNAL HEAT EXCHANGE
ABM



SALT GRADIENT SOLAR POND
INTERNAL HEAT EXCHANGE
ABM

Figure 5-1. ACTIVE SOLAR SYSTEMS (CONTINUED)

a. Collectors

The collector absorbs the solar radiation energy and converts it into thermal energy which is transferred into an air or liquid transport fluid. There are several types of collectors (Figure 5-2). Non-focusing collectors absorb the Sun's energy that falls directly on a flat absorber plate (Figure 5-3). The temperature that these collectors will provide is limited. Other collectors, even though they are designated flat plate collectors, employ curved reflectors internally which partially focus the Sun's energy on absorber tubes. These partial-focusing collectors can attain higher temperatures. External reflectors are often used with both the non-focusing and partial-focusing collectors to increase the amount of the Sun's energy that falls on their surfaces. When higher temperatures are desired, full-focusing tracking concentrators are used (Figure 5-4). These concentrators track the Sun. Some track on a single axis, some on two axes. Some focus lineraly on absorber tubes while others focus on a small point. The latter can provide very high temperatures. The most common linear-focusing collector is a tracking parabolic reflector with a fixed absorber tube mounted above the reflector. The reflector tracks the Sun on one axis while the absorber tube remains stationary. A similar collector is one that employs a fixed parabolic reflector with an overhead absorber tube which moves (one axis) so as to stay within the focal plane of the reflector. A third linear focusing collector uses a single axis tracking lens/absorber assembly. For point focus, a tracking paraboloid concentrator is used. This collector normally tracks on two axes.

The first order approximation of collector efficiency (defined as the energy supplied divided by the incident energy) may be characterized as a linear function of a collector loss parameter defined as

$$\frac{\text{Temperature of the inlet fluid - Ambient air temperature}}{\text{Incident radiation}}$$

Figure 5-5 illustrates this relationship for typical flat plate collectors. The most efficient (and the most expensive) have the flattest slope. Also indicated in Figure 5-5 are the ranges of the collector loss parameter expected for the four sites under consideration where the inlet temperature is assumed to be equal to the product temperature and ranges between 90°F and 120°F. The following notation is used:

P.M. - Portland, Me.

N.Y. - New York City

N.V. - Norfolk, Va.

J.F. - Jacksonville, Fla.

The collector heat loss parameter for the application of residual fuel oil storage clearly spans the range of efficient operation typical of flat plate collectors utilizing double-glazing or selective absorber

COLLECTOR TYPE AND NOMENCLATURE		MEDIUM	TEMPERATURE RANGE
• Non-focusing	Flat Plate	Liquid or Air	70°F to 180°F
• Partial Focusing	Flat Plate, Evacuated Tube	Liquid	180°F to 250°F
• Full Focusing Tracking Concentrators			
Linear Focus	Tracking Parabolic Reflector With Fixed Absorber	Liquid	180°F to 300°F
	Tracking Absorber With Fixed Parabolic	Liquid	
	Fresnel Lens Tracking Assembly	Liquid	
Point Focus	Tracking Paraboloid Concentraters	Liquid	Above 300°F

Figure 5-2. TYPES OF COLLECTORS

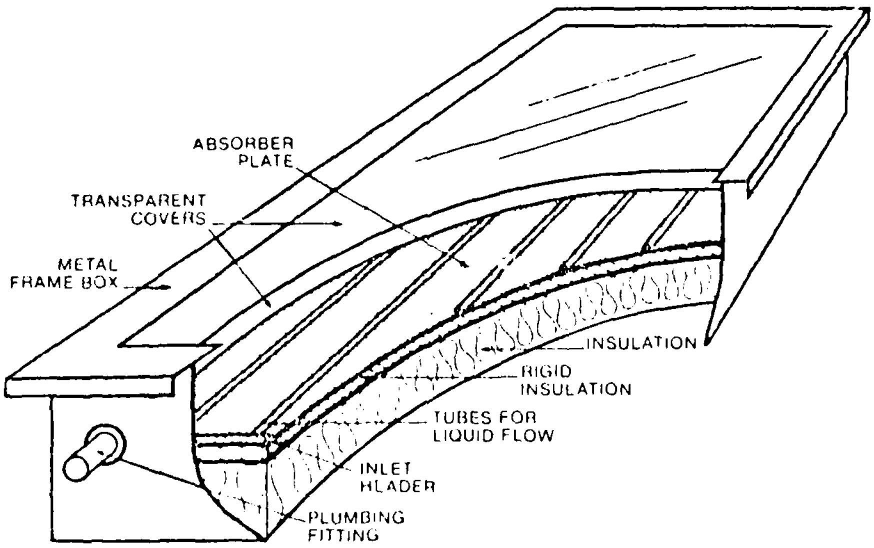


Figure 5-3a. LIQUID-TYPE SOLAR FLAT-PLATE COLLECTOR

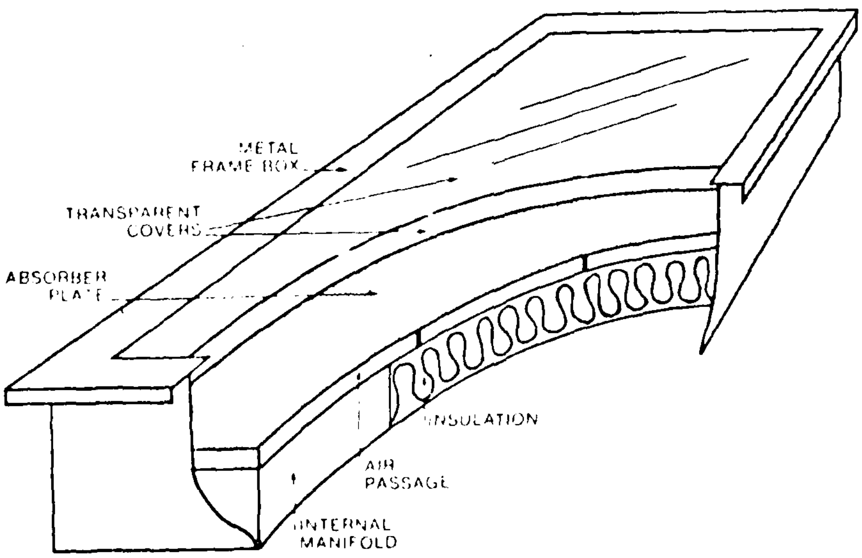
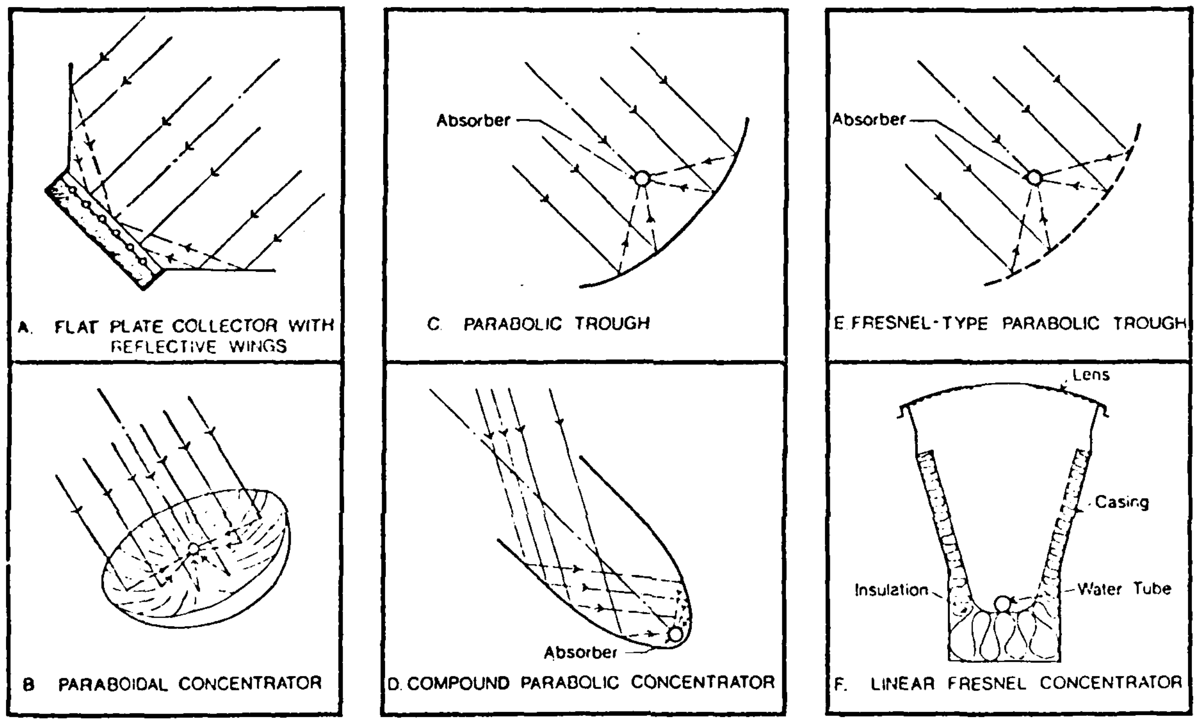


Figure 5-3b. AIR-TYPE SOLAR FLAT-PLATE COLLECTOR



Source: "ASHRAE Applications Handbook and Product Directory - 1978 Applications", American Society of Heating Refigeration and Air Conditioning Engineers, Inc.

Figure 5-4. TYPES OF CONCENTRATING COLLECTORS

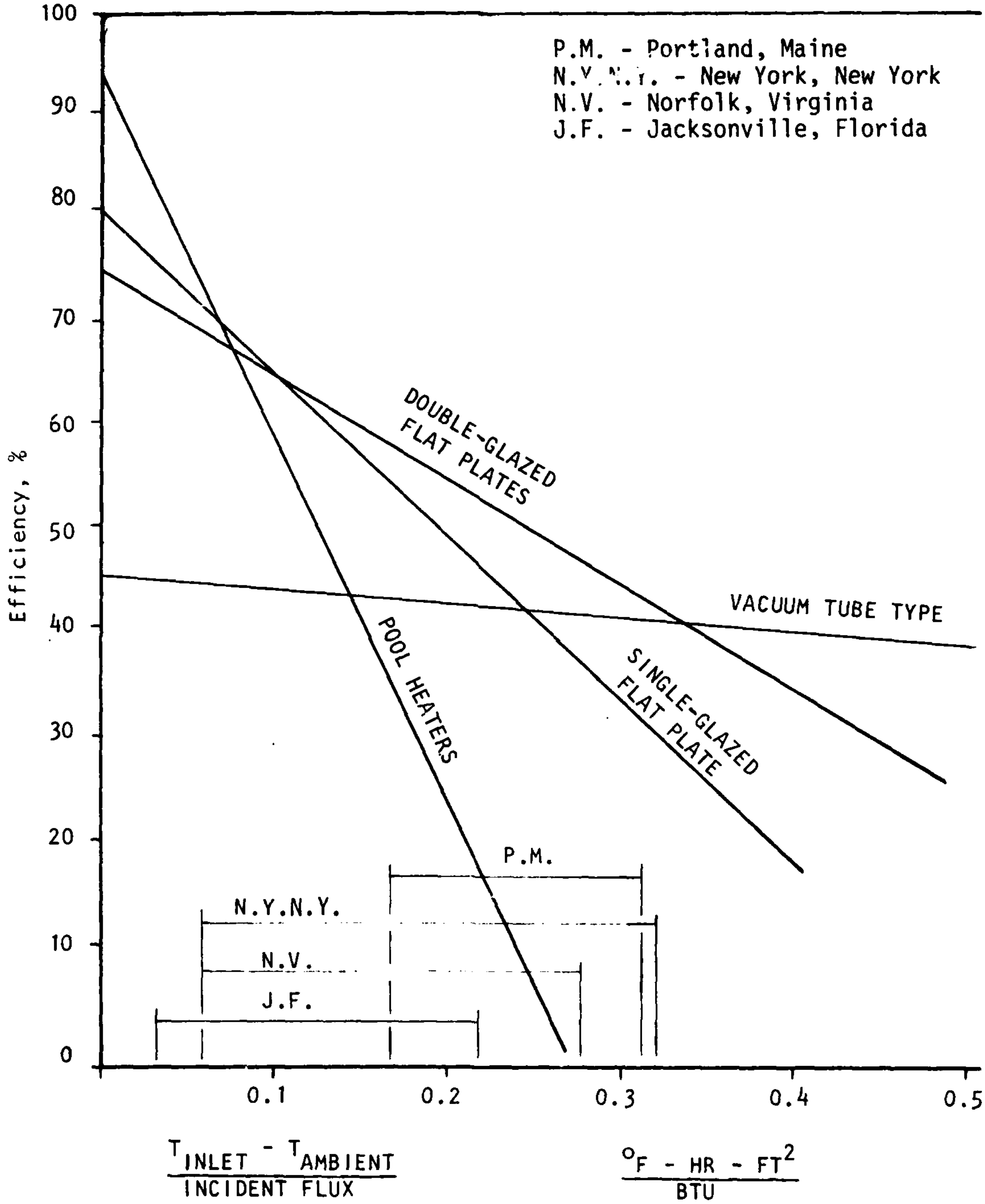


Figure 5-5. COLLECTOR EFFICIENCIES OF VARIOUS LIQUID COLLECTORS

surfaces. Concentrating collectors are capable of similar efficiency levels, but only with direct beam radiation and at unacceptable cost and complexity. Since flat plate collectors can provide the required thermodynamic capability for heating residual oil with commercial technology, consideration was not given to other collector types in this study.

b. Transport Subsystem

The function of the transport subsystem is to remove the heat from the collector and to discharge it into the product via the distribution subsystem. Selection, design, and installation of the transport subsystem critically affects overall system

- durability
- reliability
- performance
- maintenance
- cost

which must be provided under fail-safe conditions.

The transport subsystem design must meet the design criteria under three operational environments. These are:

- normal
- power OFF (freezing), and
- power OFF (stagnation).

The operational mode that most fundamentally influences the distribution system design is that of power interruption under freezing conditions. Figure 5-6 outlines the most commonly employed methods of freeze protection and some design considerations of each. In drainback systems, gravity returns the collector fluid (which is water treated with corrosion inhibitors) back to a pump and is shut down normally by a controller or abnormally by power interruption. Venting and slope of piping are most important to assure that all of the fluid will drain from the collectors.

Other systems use antifreeze solutions which are usually water and ethylene glycol or propylene glycol. Antifreeze decomposes at high temperature to form corrosive products which can damage the plumbing. This can occur during power interruption in hot weather. Therefore, the fluid must be carefully monitored for pH and depletion of corrosion inhibitors, and a backup emergency generator may be necessary.

DRAINDOWN (DRAINBACK)

- Slope of lines most important

ANTIFREEZE

- Leaks dilute solution
- Can pollute DHW
- Breaks down into corrosive products at high temperatures

CONTINOUS CYCLING

- o Rejects heat
- o Not reliable (i.e., power failure)

LOW FREEZING POINT LIQUIDS (Silicon Oil, Hydrocarbon Oils, Freon, etc.)

- o Can pollute DHW
- o Lower thermal capacity
- o Not locally available
- o Relatively expensive

Figure 5-6. METHODS FOR FREEZE PROTECTION

Cycling of the collector pump is used to prevent freezing in regions where the ambient temperature seldom gets below the freezing point. This approach may be suitable in Jacksonville, Florida. For this approach, an outside thermostat actuates the collector pump to circulate the heat transfer fluid (which may be water) through the collectors whenever the outside temperature approaches freezing. However, this is an inefficient method of freeze protection since the system rejects heat that has been previously collected, and may not be suitable for extreme colder climates. Further, failures have been noted for such systems because of power outages during freezing conditions.

Another means of freeze protection is the use of collector fluids with lower freezing points than that of water, notably silicone oils, hydrocarbon oils, freon, etc. Such fluids, however, do not have the thermal capacity (i.e., specific heat) of water, and therefore, require more flow or a larger volume for collection of an equivalent amount of energy. These fluids are relatively expensive and in many regions are not locally available. Because they are non-corrosive and are relatively stable, they may be selected for their long-term durability and reduced maintenance costs.

c. Distribution Subsystem

The function of the distribution subsystem is to transfer the thermal energy in the collector to the product to be heated. This can be accomplished by direct heating of the product as it circulates through the collector. It can also be accomplished by an intermediate fluid, e.g., air or water, that removes heat from the collector and transfers it by direct contact with the product. An indirect system utilizes a heat exchanger as an interface between the collector heat transfer medium and the product. In the selection of a distribution subsystem it is important to concentrate on design approaches that utilize, to the maximum extent possible, technologies and products familiar to manufacturers of residual oil storage tanks and ancillary components.

The primary advantage of the direct system is the elimination of the heat exchanger which can amount to 14 percent of the cost of the tank alone. Various direct methods that have been identified include:

- water bed heat exchange - uses technology common with mined storage systems, permits the use of water as a collector fluid, must be freeze protected, subject to sludge formation;

- direct pumping - employs the product as the collector heat transfer fluid, no freeze protection required, low capital cost, fouling of collector surfaces can be a problem, high pumping cost; and

- direct air pumping - uses air as the collector heat transfer medium, therefore, no freeze protection required, automatic mixing of the product, possible fouling of collector surfaces, high pumping costs.

Each of these approaches should be studied in greater detail as a viable low cost alternative to indirect systems.

The indirect system employs some type of heat exchanger interposed between the heat transfer fluid and the product. They are generally classified as:

- external heat exchangers
- internal heat exchangers
- tank wall heat exchanger

External heat exchangers are favored in the petroleum industry because leakages are easily repaired. They are somewhat more expensive than the internal heat exchanger and obviously consume more pumping energy. The internal heat exchanger is positioned in the bottom of the tank as indicated in Figure 5-7. Both the external heat exchanger and internal heat exchangers would be fundamentally similar for a solar heating system as for an oil boiler. For solar applications, allowances would have to be made for use of lower temperature fluid rather than steam. The tank wall heat exchanger is commonly employed to heat vessels, and the concept is attractive for the current application. Since the oil is initially loaded hot, the objective of the solar system would be to replenish heat lost through the walls (and floor and surface) to the external environment. A tank wall heat exchanger would assure complete extraction of the stored fluid since the walls are hot, thereby maintaining all the product in a fluid state. The tank wall heat exchanger is likely to be quite expensive but deserves further consideration because of these apparent advantages.

Figure 5-8 illustrates an emersion type heat exchanger that has already been discussed regarding its maintainability advantages. This type of heat exchanger appears to be easily interfaced with an active solar system and will be considered as a basis for the designs described herein.

Figure 5-9 illustrates a mined cavern with a water bed that results from groundwater seepage. The water bed is kept at a constant level by an automatically controlled pump. The product floats on the fixed water bed and is heated by it. Since water is an ideal heat transfer fluid for active solar systems, adequate freeze protection is necessary. The water bed is potentially easy to integrate with solar, and it might also be considered for an aboveground or belowground tank or as means of eliminating the costly heat exchanger.

5.2 PASSIVE SOLAR SYSTEM

Passive solar systems are characterized by the absence of pumps or fans for circulating the heat transfer fluid. They can also employ some

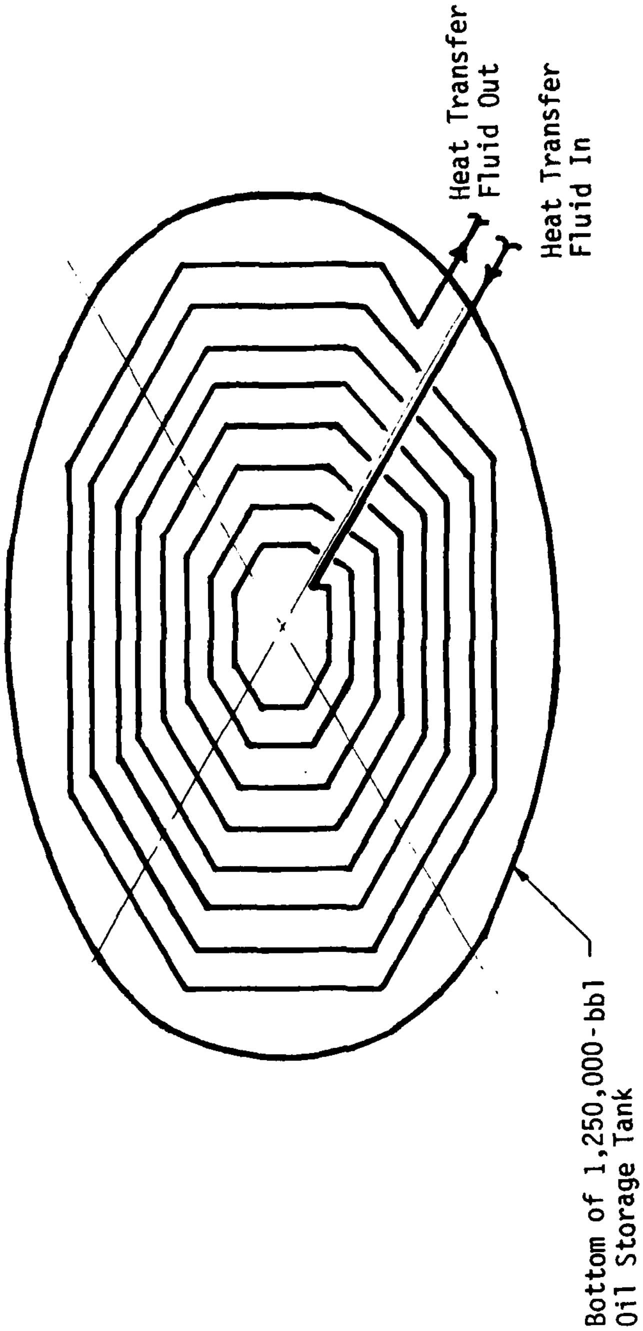
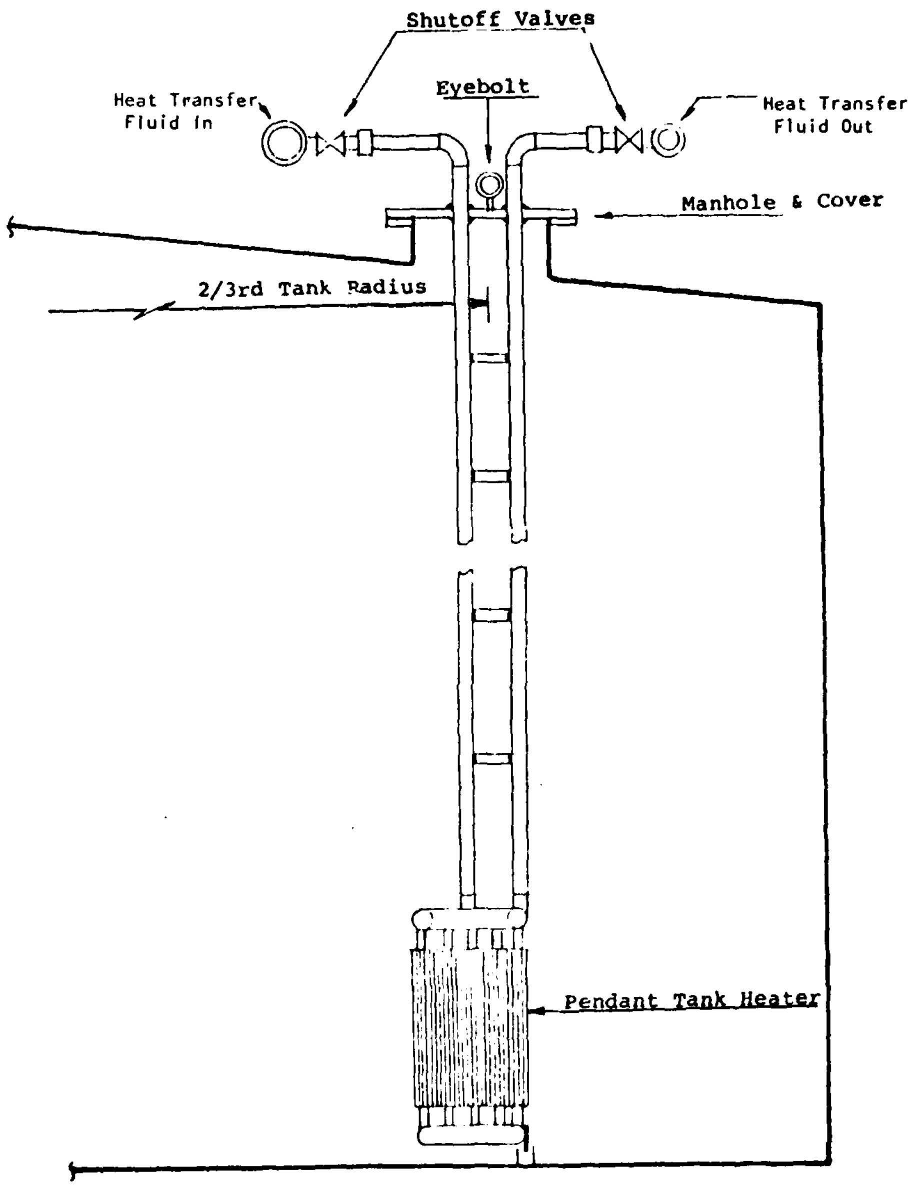


Figure 5-7. INTERNAL HEAT EXCHANGER COIL



Source: Product Specifications, Bas-Tex Corporation, 1977
Pendant Tank Heater

Figure 5-8. INTERNAL IMMERSION-TYPE HEAT EXCHANGER

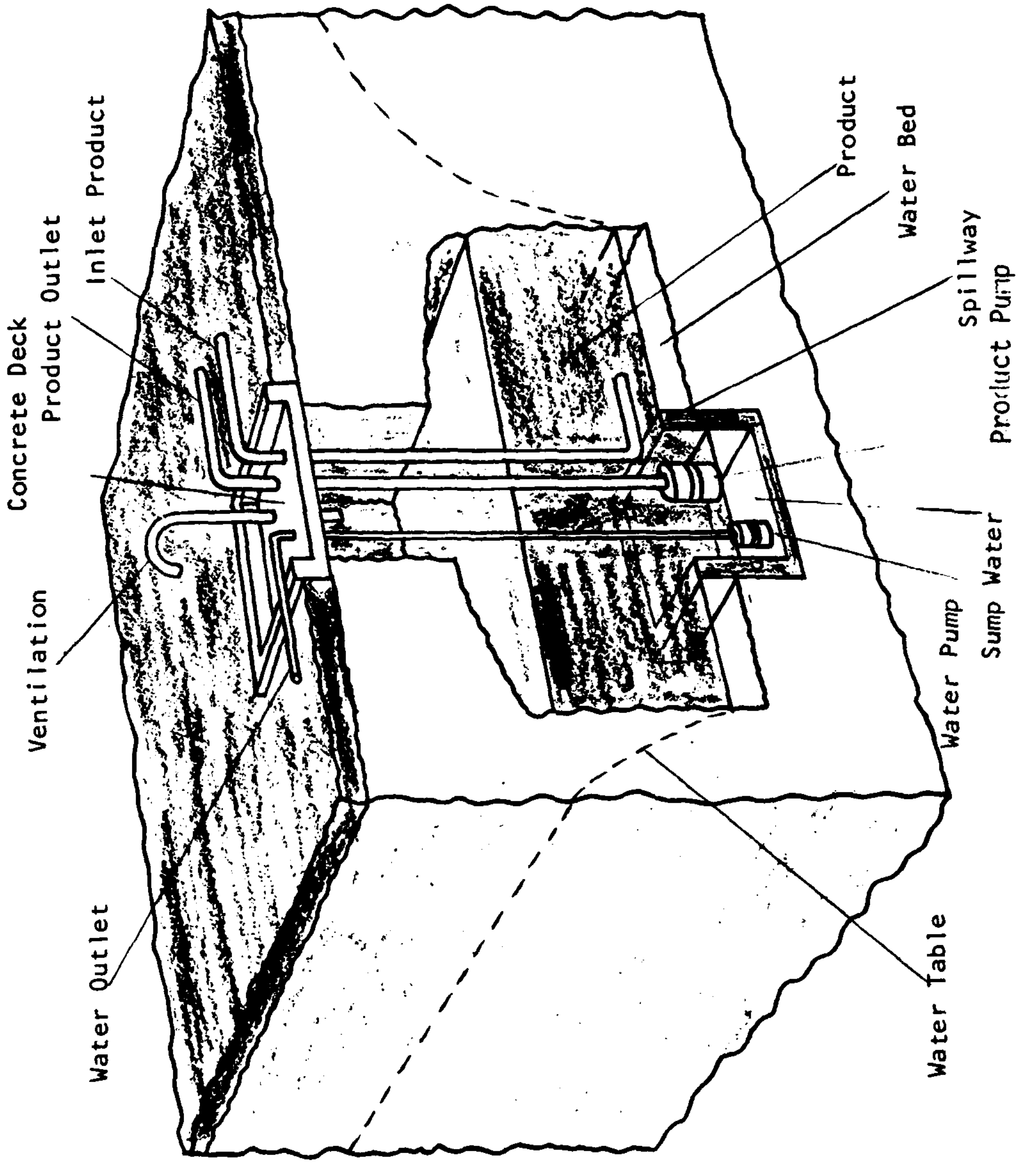


Figure 5-9. WATERBED HEAT EXCHANGER IN AN UNDERGROUND CAVERN

of the tank's existing structure to perform the collection function and distribution function (Figure 5-10). Passive concepts may be divided into direct and indirect types, just as with the active systems. As its name implies, the direct system heats the product by direct irradiation through a "sky-light." In locations where this concept is thermally viable (e.g., the net gain of solar radiation through permissible roof area exceeds the heat loss through the tank envelop) this approach has enormous cost advantages because it eliminates the necessity of an expensive heat exchanger.

Indirect systems can employ conventional flat plate collectors to heat an intermediate fluid, as with active systems. Pumping is accomplished by thermosyphon action resulting from differential elevations and fluid temperatures. An indirect gain wall is formed by a layer (or layers) of glazing attached to the tank walls. The solar radiation is transmitted through the glazing and is absorbed on the tank wall thereby elevating its temperature. Heat loss from the walls is minimized because the glazing is opaque to the longwave infrared radiation associated with the relatively low tank wall temperatures.

5.3 HEAT PUMP SYSTEMS

The heat pump has the ability to recover low grade heat (on the order of 60°F - 100°F) and elevate it to higher, usable temperature levels. They are being applied to a wide variety of applications requiring hot water up to about 210°F and where there is readily available a source of "free" heat.

The heat pump principle involves the absorption of heat, from the source, in the evaporator by the unit's working fluid (Figure 5-11). The fluid is then increased in temperature and pressurized by the compressor. It then goes to the condenser where the heat absorbed from the source and from the work of the compressor are transferred to a delivery fluid or directly to the product.

Sources of energy for a heat pump system may be harbor water, well water, or the ambient air itself (as is the case for many residential and small commercial heating/air conditioning systems) (Figure 5-12). Salt gradient and shallow solar ponds have been used as an energy source for heat pumps as have coils buried several feet beneath the soil surface (actually a type of solar collector). Perhaps the most attractive source is the thermal discharge from a nearby plant because it is reliable, the capital outlay is potentially less, and the temperature, and therefore, the performance is higher. Since oil storage facilities are generally located in or near industrial areas, the potential for a nearby power plant or industrial discharge is great. Because this approach is so site specific, it must be considered on a case-by-case basis.

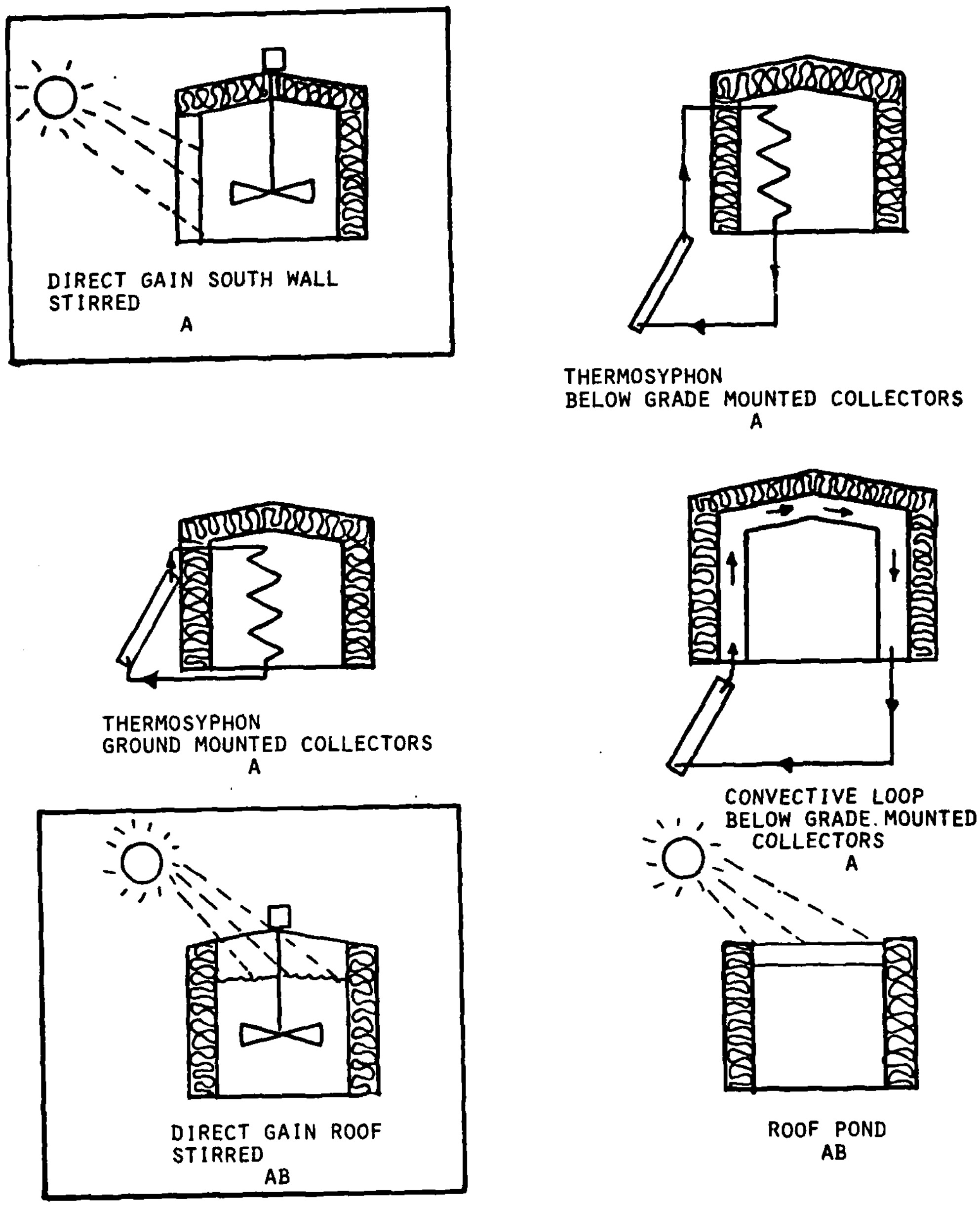
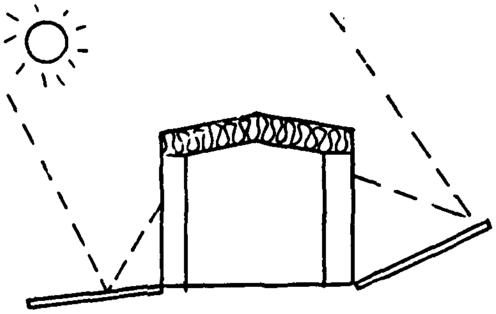
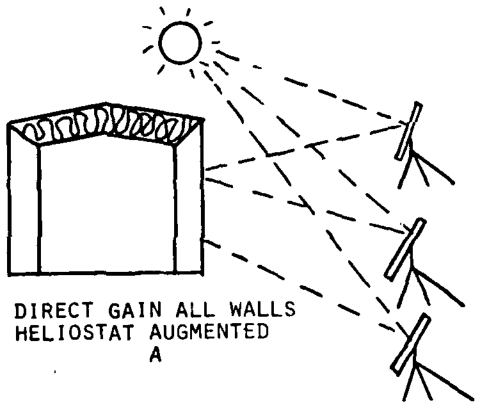


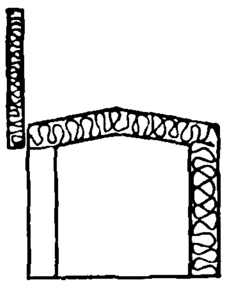
Figure 5-10. PASSIVE SOLAR SYSTEMS



DIRECT GAIN NORTH AND SOUTH WALL
REFLECTOR AUGMENTED
A



DIRECT GAIN ALL WALLS
HELIOSTAT AUGMENTED
A



DIRECT GAIN SOUTH WALL
MOVABLE INSULATION
A

Figure 5-10. PASSIVE SOLAR SYSTEMS (CONTINUED)

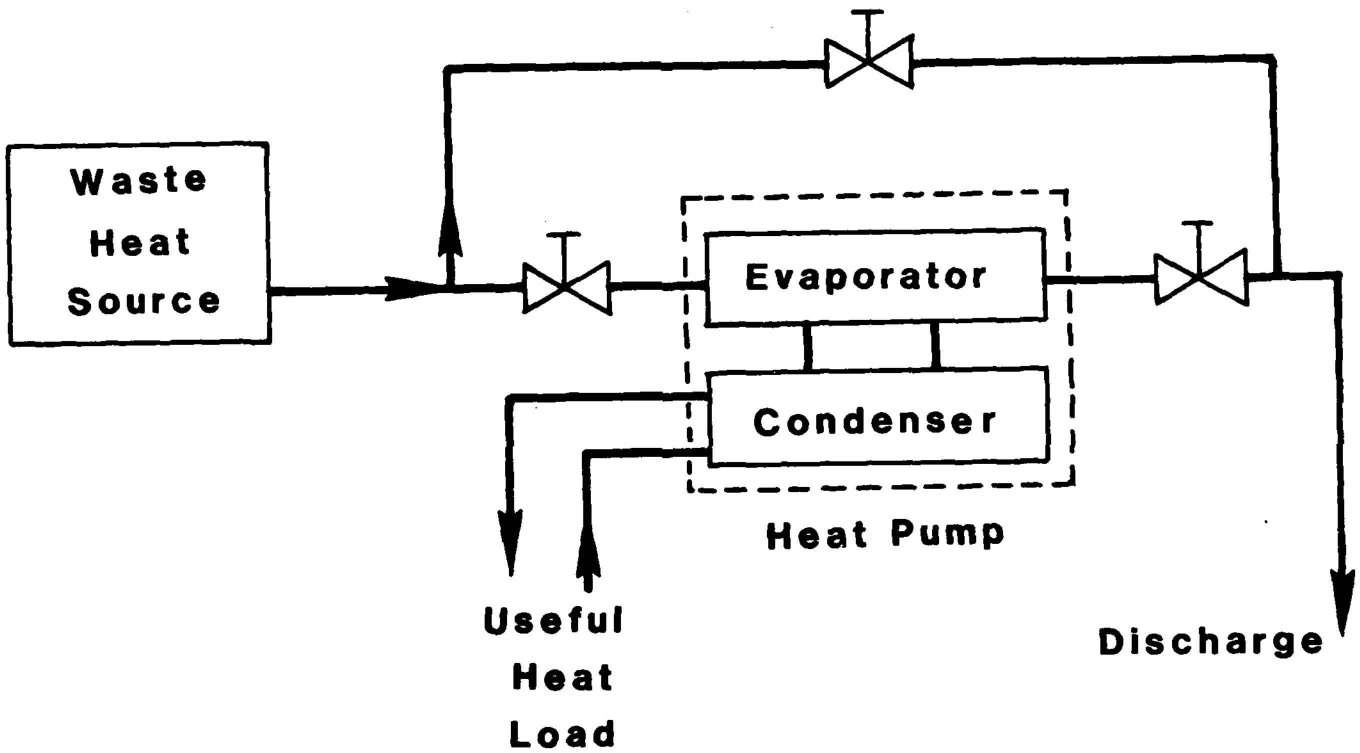


Figure 5-11. HEAT PUMP

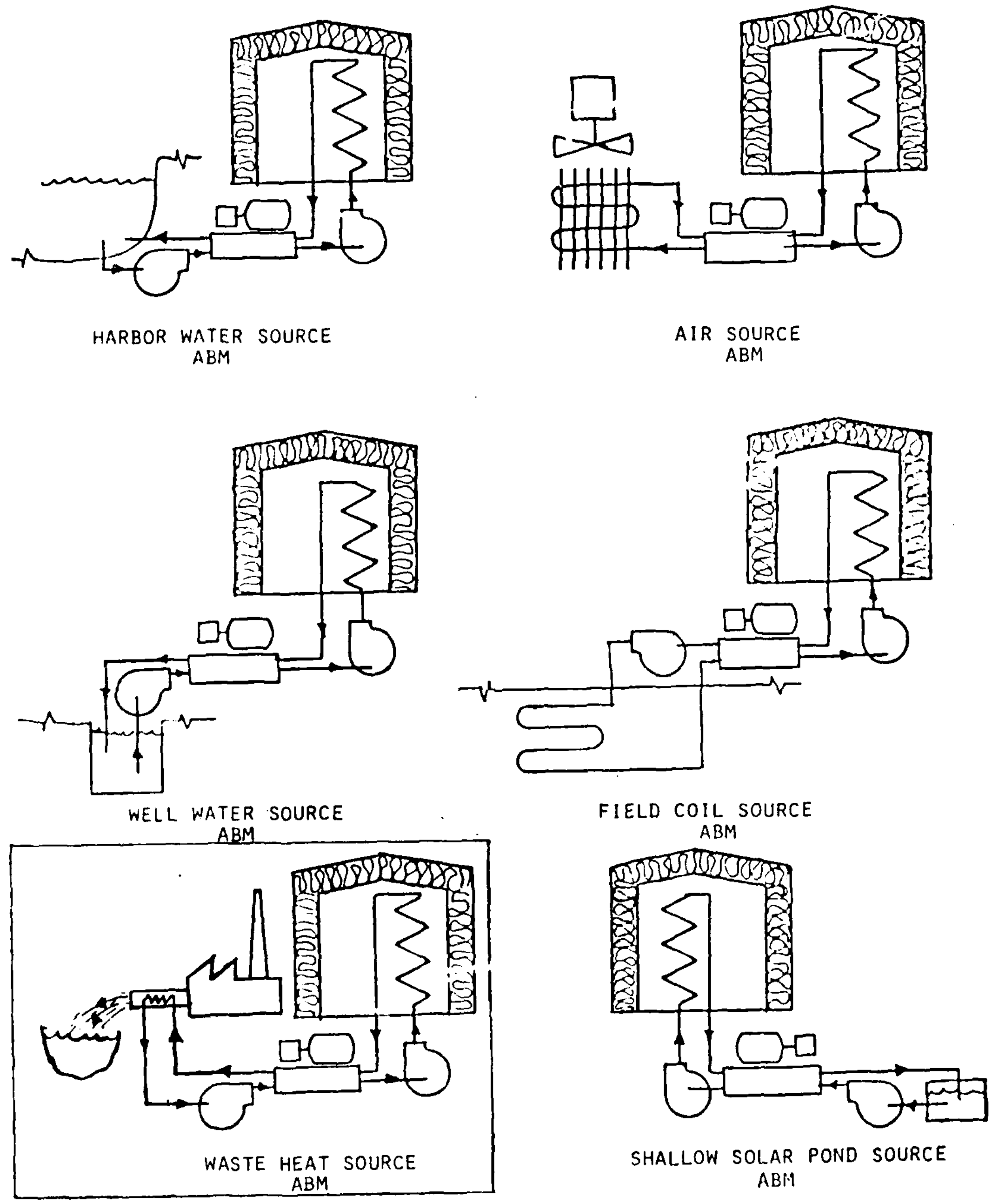


Figure 5-12. HEAT PUMP SYSTEMS

CHAPTER 6
SOLAR SYSTEM DEFINITION

In this chapter the technical and cost characteristics of selected system concepts are defined in greater detail as examples of designs that may be considered for residual oil heating. It must be cautioned that there are many opportunities that have not been considered for cost reduction through subsystem selections and tradeoff. These other considerations should be studies before a committment is made for final design. Whenever possible, alternative approaches are identified and discussed.

6.1 ACTIVE SYSTEMS

a. Systems Description

The active systems selected for detailed consideration uses the closed-loop transport subsystem employing a non-freezing fluid as the heat transfer medium (Figure 6-1). This type of system has most frequently been the choice of designers because of its relatively low cost and design flexibility. Designs are considered where the collector is located on the tank roof or on the ground. To avoid fluid deterioration under stagnation conditions, an emergency auxiliary power supply may be necessary.

Where temperatures are milder, the drainback system is the preferred choice if the collectors can be roof mounted (Figure 6-2). Freeze protection is afforded by the draining of collectors into the drainback reservoir. The collectors must be capable of withstanding stagnation (no flow) conditions if a power outage occurs during an extreme summer day. High head pumps are required to overcome the large static head upon startup. Careful design and installation of piping is required to assure drainage during pump shutdown and complete air purging on collector startup.

b. Array

Whenever possible, the roof-mounted collector array was chosen as the preferred collector placement, although at some sites this resulted in considerable additional cost in tank structure. The advantages of this arrangement are:

- collector shading from nearby tanks or other structures is not a consideration
- additional valuable land is not required for collector siting

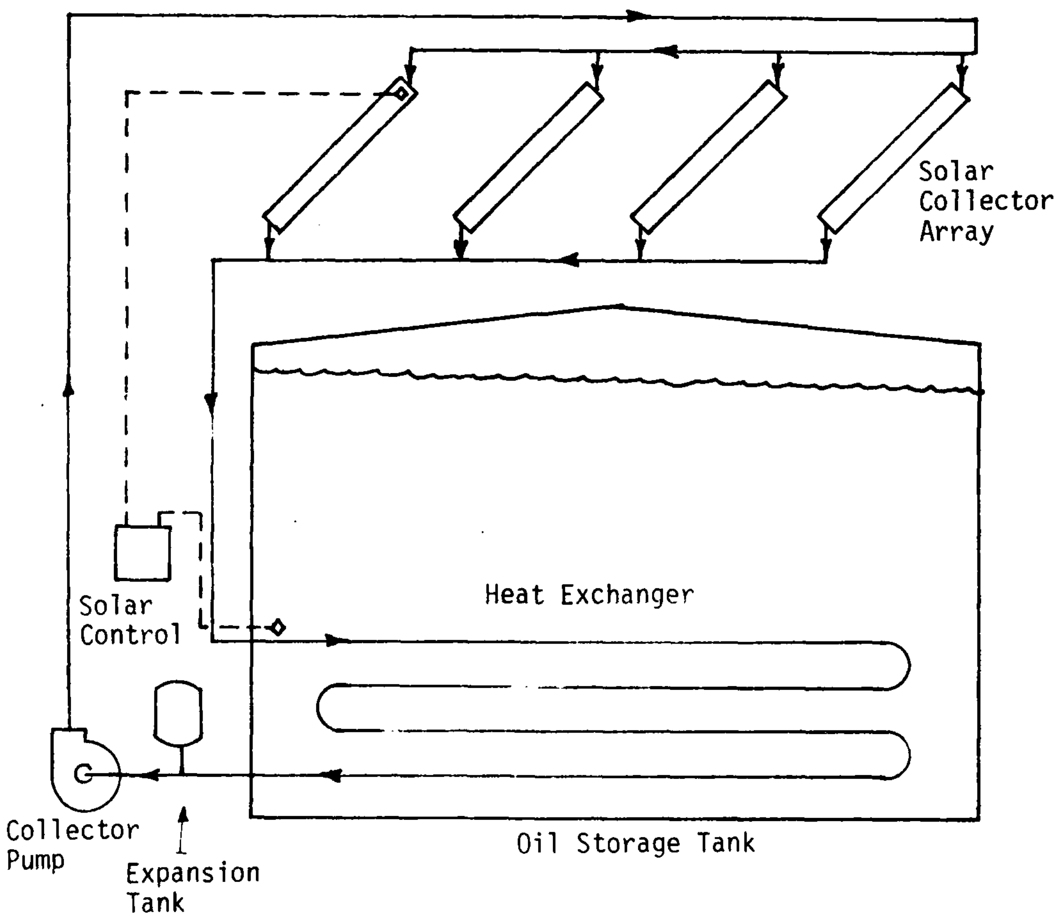


Figure 6-1. CLOSED-LOOP ANTIFREEZE SYSTEM SCHEMATIC

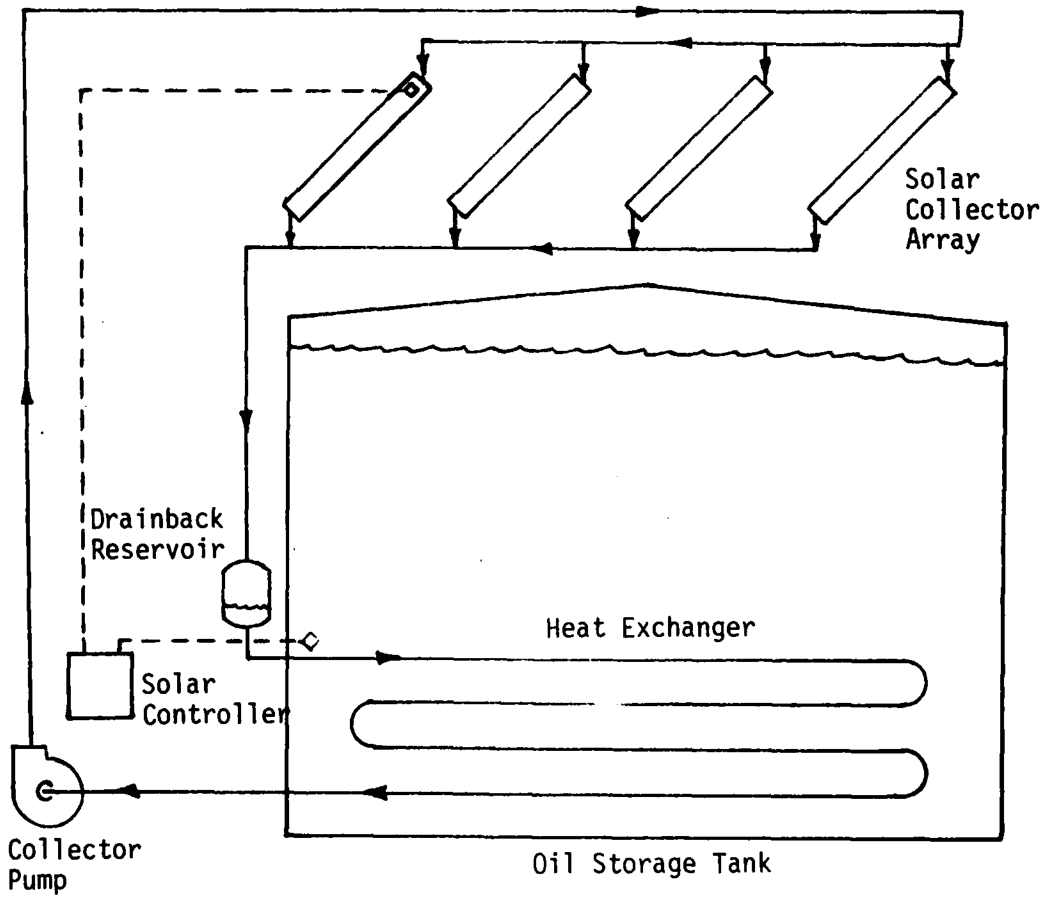


Figure 6-2. DRAINBACK SYSTEM SCHEMATIC

- piping runs are minimized
- permits convenient interfacing with immersion type heat exchanger
- permits use of drainback system

The roof-mounted array does impose additional considerations on tank design and erection procedures. Some of these will be discussed in subsequent paragraphs.

(1) Detailed Description: Collector area requirements were determined in paragraph 7.2b. Figure 6-3 illustrates a view of the collector field in a location and at a product temperature where the tank roof area is insufficient for supporting the required number of collectors (Portland, Me. at a product temperature of 110°F). In this case, some ground mounting is the only feasible alternative for achieving the desired collector area.

To permit detailing of system design features and cost, a modular design concept was developed. Each module (a system will be comprised of several modules) is essentially an independent active solar system containing the collector array, closed-loop transport system controls, and an immersion type heat exchanger. This modular design facilitates design, fabrication, and maintenance, while providing redundancy. Figures 6-4a and 6-4b illustrate the module for a roof-mounted configuration. Ground-mounted arrays will still employ the immersion type heat exchanger but longer transport lines to the top of the tank will be required. Spacing between the collectors is based upon the requirement to avoid shadowing between 9:00 a.m. and 3:00 p.m. for Portland, Me. on December 21 (see paragraph 7.4). Figure 6-4c illustrates placement of modules on the tank roof.

(2) Collector: To aid in the detailed characterization of the active heating system, the LOF Sunpanel was selected as being representative of flat plate collectors in which design options were available to improve performance. Future studies should consider other collectors as well as assure that the maximum in cost effectiveness is achieved. Figure 6-5 illustrates a cross-section of the double-glazed version of the LOF collector. The present study considered only the single-glazed model, without and with selective surface.

The collector design is based upon a heavily ribbed extruded frame construction. Top and bottom panels are sealed against the elements, yet can be removed if necessary. Insulated support of absorber plate and cover plate(s) minimize heat loss through the frame. Three inches of low binder fiberglass insulation under the absorption plate and a special side insulation minimizes heat loss. An all copper fluid passage is soldered to the embossed copper absorber plate. A parallel tube pattern provides uniform flow through each panel and the panels can be connected in either series or parallel arrangements. The absorber is

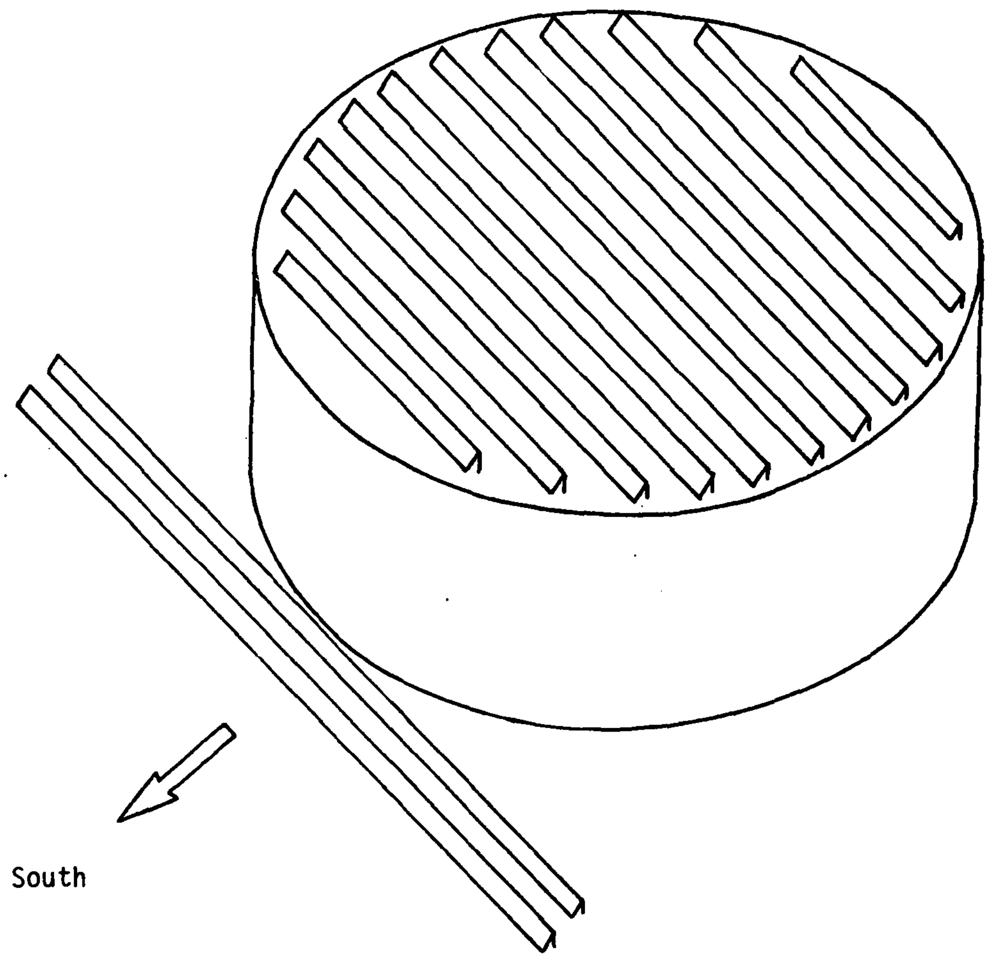


Figure 6-3. ACTIVE SOLAR COLLECTOR ARRAY
PORTLAND, MAINE
110°F

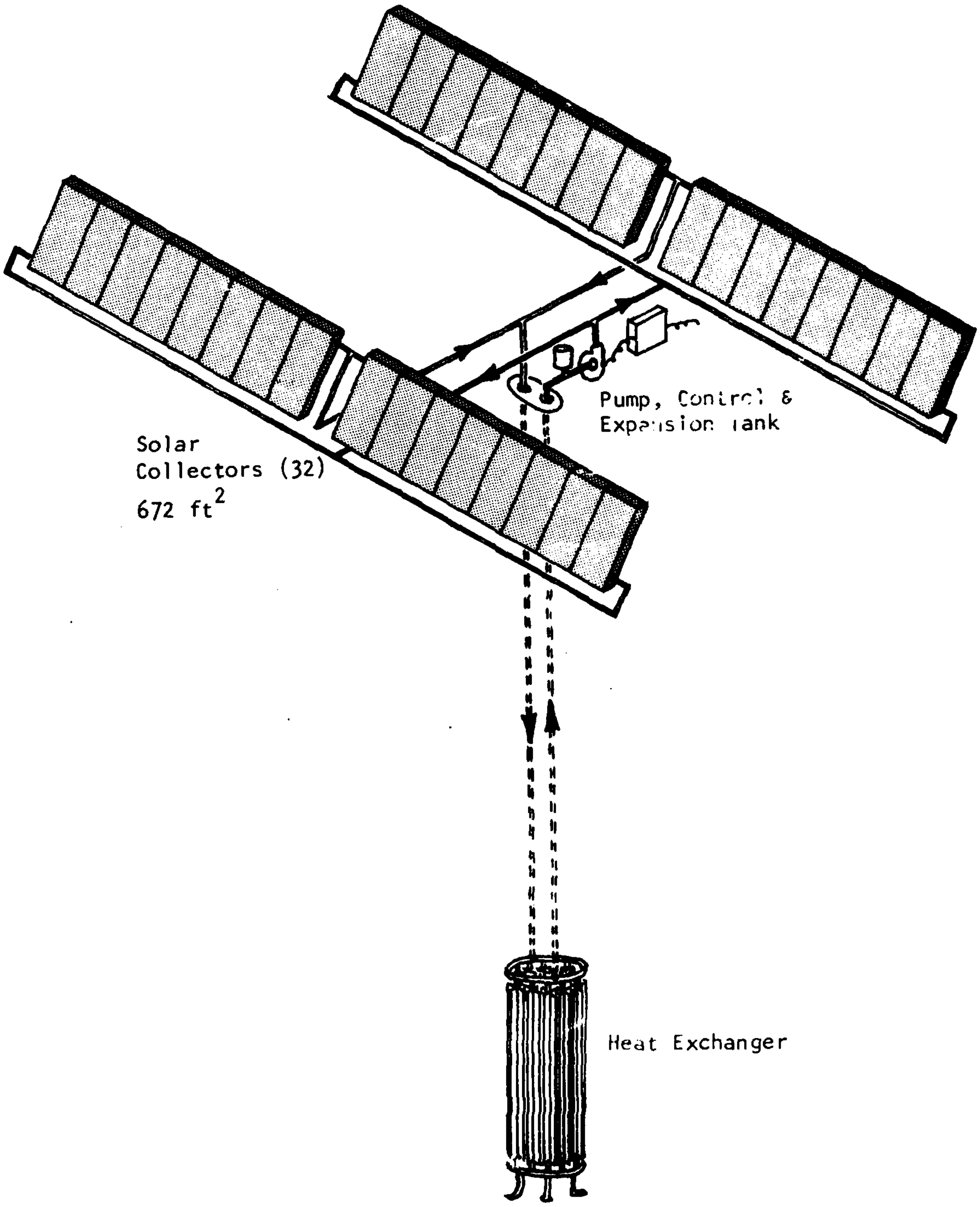
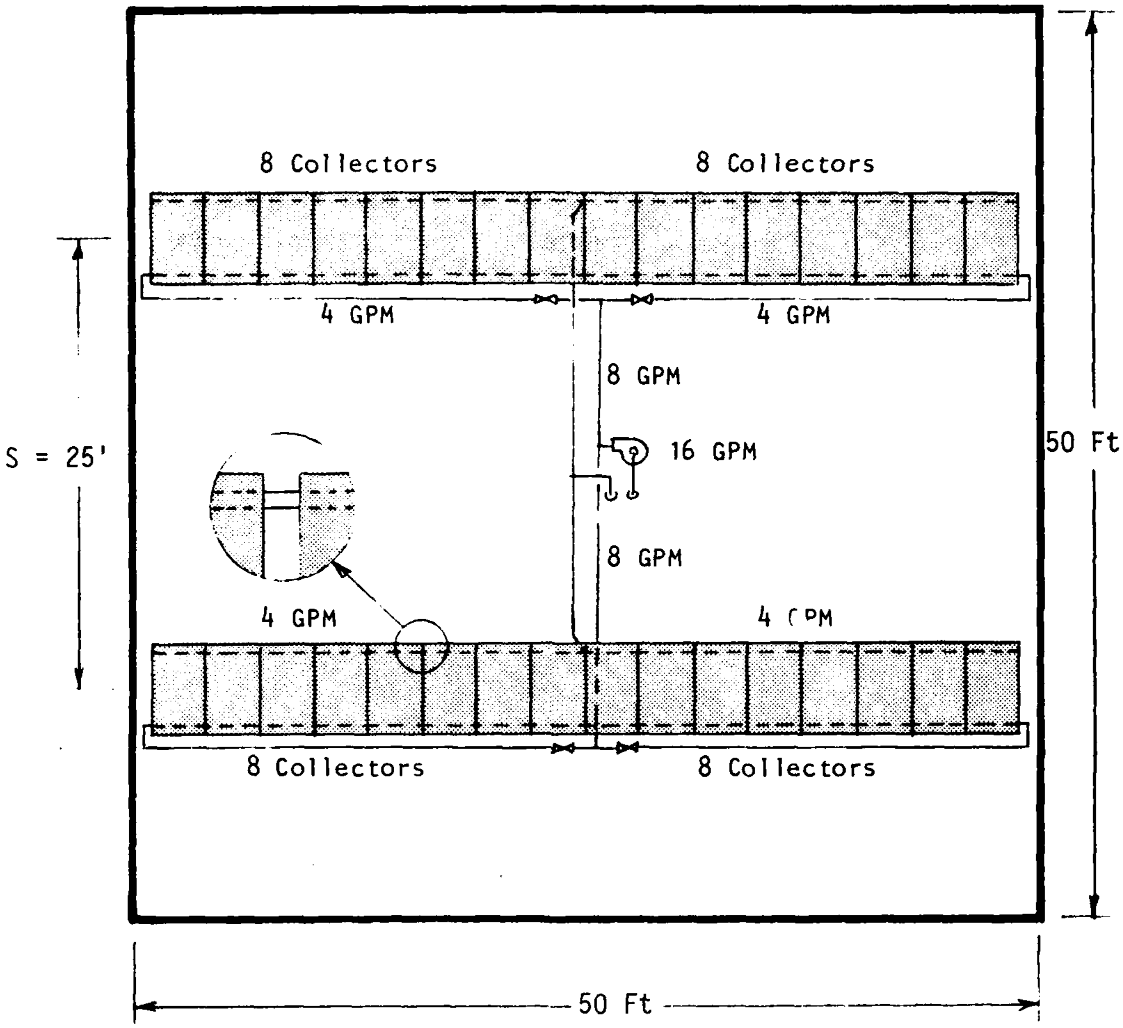


Figure 6-4a. ACTIVE SYSTEM MODULE

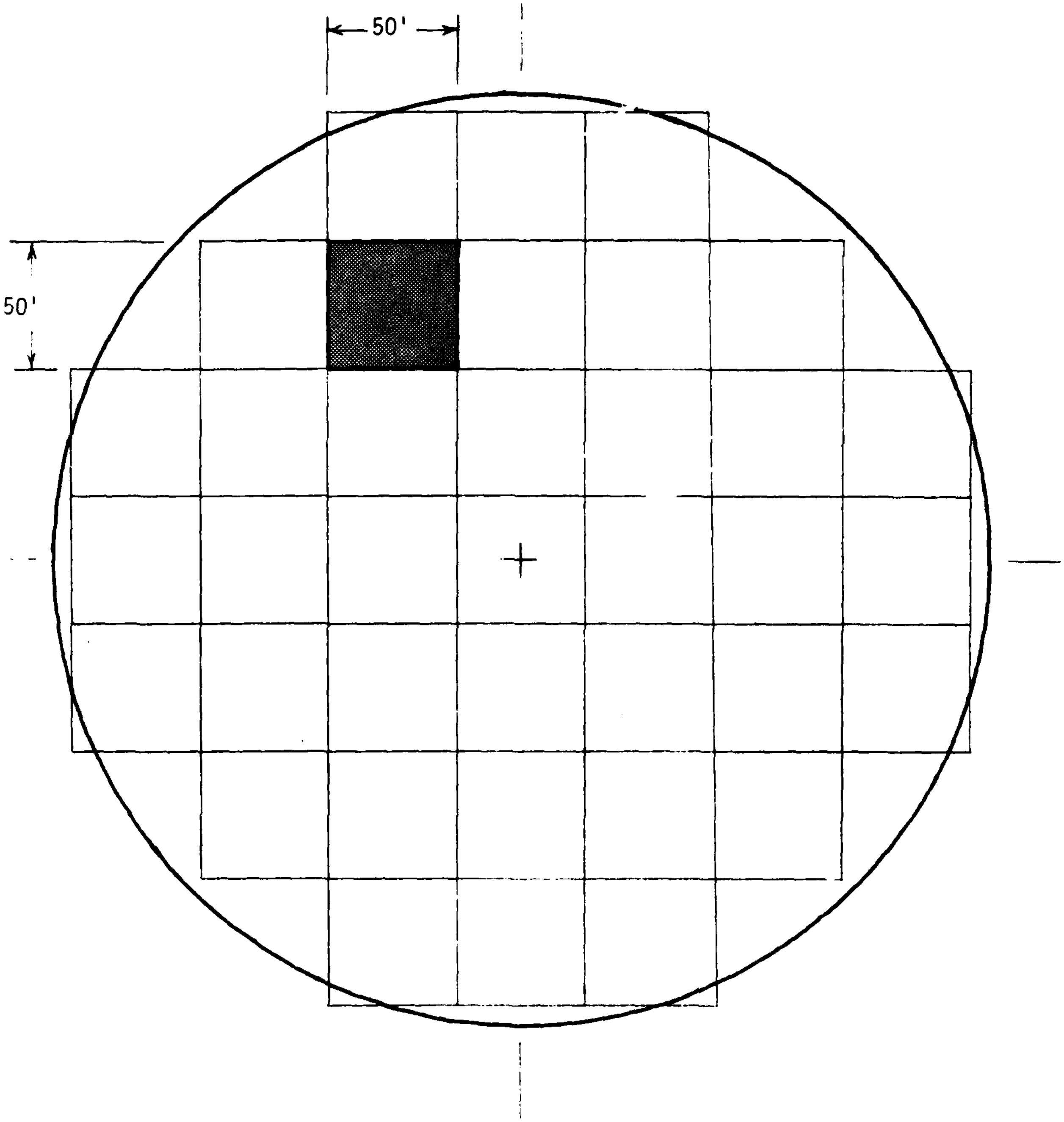


Collector Area - 672 ft^2

Number of Collectors - 32 (16 collectors per row)

Roof Area - 2500 ft^2

Figure 6-4b. PLAN VIEW OF ACTIVE SYSTEM ROOF MODULE



Total Collectors = 1184

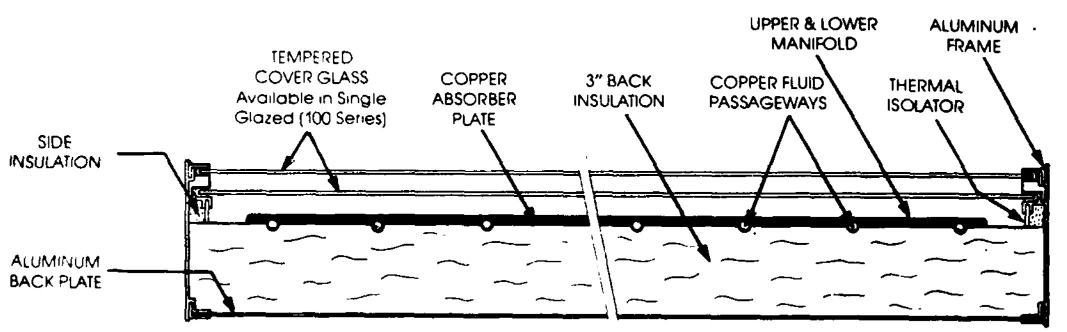
Total Area = 24,804 ft^2

Figure 6-4c. PLAN VIEW OF ROOF ILLUSTRATING MODULE PLACEMENT

Table 6-1. LOF COLLECTOR SPECIFICATIONS

SPECIFICATIONS	100 SERIES
COVER GLASS —	1
LOF Tempered Clear Float	⅛"
LOF Tempered Low Iron	⅛"
ABSORBER PLATE — All Copper	■
ABSORBER PLATE COATINGS —	
Non-Selective Black Velvet Paint	■
Selective Black Chrome Plating	■
HEAT TRANSFER FLUID SYSTEM — All Copper	■
FRAME and BACK PANEL — Aluminum	■
BACK INSULATION — Treated Fiberglass	3"
RECOMMENDED FLUID FLOW RATE	0.5 gpm
PRESSURE DROP AT RECOMMENDED FLOW (glycol water)	0.09 psi
DESIGN PRESSURE	100 psi
TEST PRESSURE	200 psi
BURST PRESSURE	450 psi
NO-FLOW PROTECTION REQUIRED	None
EFFECTIVE AREA 19.3 sq ft	■
MAXIMUM INTERNAL TEMPERATURE (no-flow)	400°F
PERFORMANCE TEST SPECIFICATION — NBSIR 74-635 ASHRAE 93-77	■
ENVIRONMENTAL CONDITIONS — -40°F to +120°F	■
MAXIMUM WIND or SNOW LOAD	30 lbs SF
FLUID CONNECTIONS —	
Brass 45° Flared — Optional	■
½" Copper Tube	■
INSTALLATION ORIENTATION - Short Side horiz	■
MINIMUM TILT ANGLE (to allow complete draining of panel) — From Horizontal	10°
MAXIMUM TILT ANGLE	90°
MOUNTING — 4-Point, Perimeter on Structural Frame	■
PANEL WEIGHT	90 lbs
INSTALLED LOAD — lbs SF	4.3
SHIPPING WEIGHT	110 lbs

Source: "LOF Solar Energy Systems" Libby-Owens Ford Company Glass Div.



SunPanel Collector 200 Series (double glazed)

Figure 6-5. SECTION OF LOF DOUBLE-GLAZED COLLECTOR

available with either a selective or non-selective coating. The non-selective is a baked-on black velvet paint with an absorption factor of 0.97 and an emittance of 0.89. The black chrome selective coating has an absorption factor of 0.95 and an emittance of 0.1.

LOF Float Glass or low iron, high-efficienty glass is available to meet a wide range of performance requirements. Glass covers are tempered for safety considerations. Tempered glass is impervious to the ultraviolet rays of the sun, and retains its strength even when exposed to the high temperatures generated inside the collector. One of two glass cover plates may be specified. The addition of a second cover plate creates an air space between the glass, providing thermal insulation which retains heat in cool ambient conditions. Two layers of glass, with an air space between them, give superior thermal insulation, retaining heat in cool ambient situations. Specifications of the single glazed version are provided in Table 6-1.

Two versions of the LOF collector were considered in the present study. The first was the single-glazed collector with the flat black absorber; the second was the single-glazed collector with the selective surface. The following performance and cost factors apply to the collectors.

Model No.	$F_R\ (\tau\alpha)$	$F_R U_L$	Cost
120	0.691	1.30	$210 per collector
121	0.71	0.77	$250 per collector

In a separate study, various collectors were examined to determine the minimum cost collector that would meet space heating load of 205 (10^6) Btu/yr at a Birmingham, Alabama site. Table 6-2 presents the cost of each collector[6], the values of the performance parameters and the collector cost to achieve 60 percent solar heating fraction. This study is presented only as an indication of the cost savings potential achievable through consideration of the various performance and cost factors associated with the many collectors now on the market. Obviously other selection criteria must be considered as well as cost and performance. Some of these are:

- durability
- maintainability
- installation requirements

[6] "Solar Products Specifications Guide," Solar Age Magazine, Solar Vision, Inc. Church Hi-1, Harrisville, New Hampshire, 03450.

Table 6-2. COLLECTOR COSTS TO MEET A SPACE HEATING LOAD IN BIRMINGHAM, ALABAMA

Manufacturer & Collector Name	$F_R\tau\alpha$	F_RU_L	Collector Area (Wet) (ft^2)	Cost Per Collector	Cost Per ft^2 of Collector	Collector Area Required for f_s = 60%	Collector Cost for f_s = 60%
Libby-Owens Ford Sunpanel 120	.720	1.30	19.25	$270	$14.00	1700	$23,800
Libby-Owens Ford Sunpanel 121	.71	.77	19.25	312	16.20	1100	17,820
Libby-Owens Ford Sunpanel 220	.70	.934	19.25	312	16.20	1250	20,250
Libby-Owens Ford Sunpanel 221	.65	.66	19.25	360	18.60	1150	21,390
National Solar Corp. NSC-100	.805	.958	21.72	515	23.70	1000	23,700
Solar Thermal Systems, Paystar 1600	.76	.727	21.10	433	20.50	950	19,475
Solar Thermal Systems, Paystar 1600 TLS	.76	.828	21.10	445	21.10	1000	21,100
Solar Unlimited Suncatcher H-1	.72	.98	16.70	380	22.80	1240	28,272
Solar Unlimited Suncatcher H-2	.81	1.33	16.70	280	16.80	1340	22,512
U.S. Solar Corp., Eagle	.73	1.05	32.00	364	11.40	1300	14,820

Table 6-2. COLLECTOR COSTS TO MEET A SPACE HEATING LOAD ON BIRMINGHAM, ALABAMA

Manufacturer & Collector Name	$F_R\tau\alpha$	F_RU_L	Collector Area (Wet) (ft^2)	Cost Per Collector	Cost Per ft^2 of Collector	Collector Area Required for f_s = 60%	Collector Cost for f_s = 60%
Ametex, Sunjammer	.76	.75	23.46	$390	$16.61	1000	$16,600
Approteck, Solar-Solaristocrat	.572	.987	23.44	325	13.90	2000	27,800
Enthane, Solector Liq. Col. (A.G.)	.68	.80	18.70	405	21.70	1200	26,040
Enthane, Solector Liq. Col. (S.G.)	.726	.87	18.70	355	19.00	1100	20,900
Grumman, Sunstream 121	.770	.84	18.60	429	23.10	1000	23,100
Grumman, Sunstream 132	.770	.84	29.70	620	20.90	1000	20,900
Grumman, Sunstream 321	.762	.911	18.90	380	20.10	1060	21,306
Grumman, Sunstream 322A	.754	.869	30.00	565	18.80	1050	19,740
Grumman, Sunstream 432A	.710	.660	30.00	662	2[illegible].10	1000	22,[illegible]00
Grumman, Sunstream 421A	.710	.660	18.90	580	30.70	1000	30,700
Grumman, Sunstream 232	.715	.604	29.70	734	24.70	1000	24,700
Grumman, Sunstream 221	.715	.604	18.60	501	26.90	1000	26,900
Halstead, Mitchell, Sanceiverll	.761	1.090	17.20	380	22.10	1200	26,520
Heilosystems, MT-200-C	.605	.947	23.78	400	16.80	1700	28.560

Table 6-2 Continued.

- company stability
- warranties

and so forth.

(3) Mounting: A detailed study was conducted to insure structural compatibility of the collector mounting system with the tank and to identify increased tank costs due to roof-mounted arrays. As a basis for the study it was assumed that the tank is to be fabricated by Chicago Bridge and Iron Company (CBI) with the following design characteristics:

- Material - ASTM A588, Grade A or B (COR-TEN), Corrosion Resistant

  F_t = 70,000 psi Ultimate Tensile

  F_y = 50,000 psi Minimum Yield

  $E = 30 \times 10^6$ psi Modulus of Elasticity

- Geometry

  Diameter - 375'
  Height - 64'

- Construction (Pertinent to Solar)

  Roof Decking - 3/16" plate
  Roof Support - Beam/Column
  Intermediate Purlin Spacing - 7' sq

Structural analyses to determine incremental costs due to solar requires a detailed computer model of the tank roof and support structure. As a courtesy, these analyses were conducted by CBI using values of applied dead loads and wind loads provided by the Alabama Solar Energy Center.

The tilt angle required in Portland, Me. results in the largest panel support structure. Since Portland also required the greatest spacing between arrays (to preclude shadowing), New York represented the greatest panel density, and, therefore, load to be supported by the tank roof. Table 6-3 presents the collector quantities and row spacing required (or permitted) for each site.

Table 6-3. COLLECTORS REQUIRED (T-120°F)

Location	Tank Roof-Mounted	Ground-Mounted	Row Spacing
Portland, Me.	1463	660	20'
New York, N.Y.	1560	0	14'
Norfolk, Va.	1248	0	12'
Jackvonville, Fl.	1025	0	7'

The number of rows required to cover one-half the roof structure area dictates the dead load criteria for the entire roof/support structure at all locations. This loading method can be refined in final design after cost-effective tradeoffs are made for geographical locations versus design commonality and fabrication cost savings.

The large quantity of panels required for installation indicates array subassembly at the manufacturer's plant or the frame fabricator's plant. If a support frame is designed to contain panels in modules of four each, cost savings will result in:

- frame fabrication
- panel/module shipping
- site erection

The optimum module size is four panels; i.e., 1100 lbs per module and 12 feet long. This module length will assist and accommodate the curved surface thus simplifying design, fabrication, and installation.

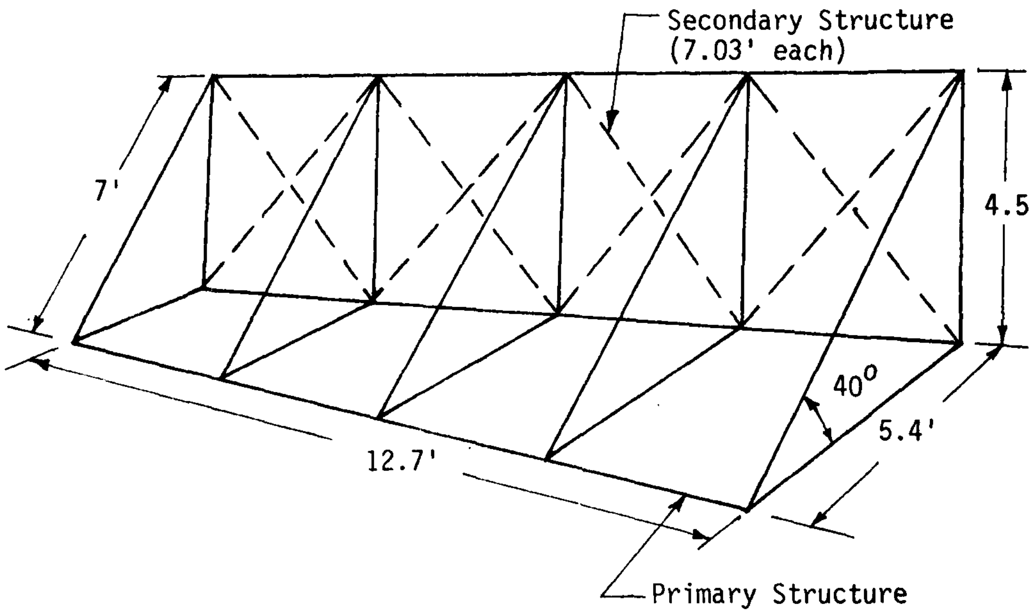
Support frames will be welded COR-TEN, equal leg angles. Figure 6-6 illustrates the mounting structure designed to the above criteria. Table 6-4 summarizes the loads for each site and the incremented cost of the tank associated with additional roof support structure.

Table 6-4. IMPOSED ROOF LOAD AND INCREASED TANK COST

Location	Dead Load + Live Load	Tank Cost Increased
Portland, Maine	50 psf	$312,500
New York, New York	50 psf	$312,500
Norfolk, Virginia	25 psf	0
Jacksonville, Florida	25 psf	0

Design of the panel support structure was based on the following design criteria.

- Dead Load - Panel weight of 90 lbs
- Live Load - Snow weights can be disregarded on the panels due to the tilt angle $\alpha = 40^{\circ}$
- Wind Load - Will dictate sizing of the panel support structure

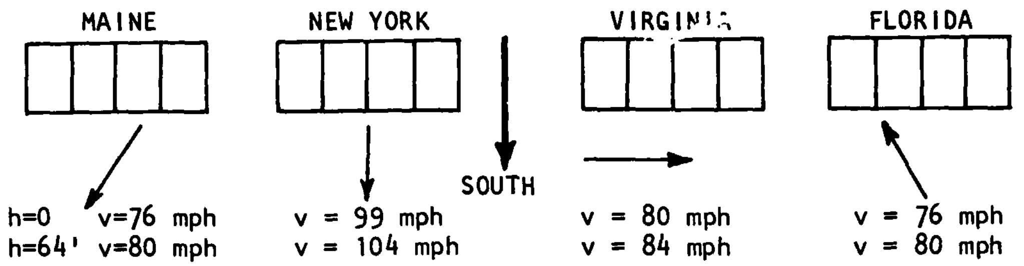


Total Weight (including panels) = 328,350

Applied Dead Load = 6 psf

Figure 6-6. COLLECTOR SUPPORT STRUCTURE

The wind load analysis is based on wind direction and speed as indicated below:



The New York location will impose the design criteria since it has the highest wind velocity (v=104 mph).

The assumption of a frame fabricated from 2" X 2" X ½" angles is most adequate. Maximum weight of panel support structure is 185 lbs/panel.

Table 6-5 presents a cost summary of the panel support structure and Table 6-6 summarizes the resulting frame cost. These costs do not include engineering design.

Table 6-5. SUMMARY OF FRAME COST

Location	Support Weight	Cost	Net Cost/Panel
Maine	185 lbs.	\$1.50/lb	\$278.00
New York	185 lbs.	\$1.35/lb	\$250.00
Virginia	185 lbs.	\$1.20/lb	\$220.00
Florida	185 lbs.	\$1.08/lb	\$200.00

Table 6-6. COST SUMMARY OF PANEL SUPPORT STRUCTURE

Location	Material Cost	Fabrication Cost	Erection Cost	Total Cost
Maine	50¢/lb	80¢/lb	20¢/lb	\$1.50/lb
New York	50¢/lb	70¢/lb	15¢/lb	\$1.35/lb
Virginia	50¢/lb	60¢/lb	10¢/lb	\$1.20/lb
Florida	50¢/lb	50¢/lb	8¢/lb	\$1.08/lb

The roof-mounted support structure will be used as a design basis for the ground-mounted array structure. The slight advantage in reduced

wind loads at ground level could be considered during final design, but were not considered in this preliminary study.

Soil conditions at the four geographical locations are unknown, which affects pier compression settlement) and surface erosion. However, the most significant foundation design parameter is pier lift loads. This load will establish a conservative cost estimate for foundations. A perimeter pad is recommended to eliminate erosion problems. Figure 6-7 illustrates a cross-section of the ground-mounted support structure and Table 6-7 provides a cost summary.

Table 6-7. COST SUMMARY OF GROUND-MOUNTED SUPPORTS

Location	Panel Support Cost	Foundation Material Cost	Foundation Labor Cost	Total Cost/Panel
Maine	\$278.00	\$9.50	\$2.00	\$289.50
New York	\$250.00	\$9.50	\$2.00	\$261.50
Virginia	\$222.00	\$9.50	\$2.00	\$233.50
Florida	\$200.00	\$9.50	\$2.00	\$211.50

c. Transport System

Heat Transfer Fluid: The choice of heat transfer fluid is critical to the cost, performance, and durability of an active solar system. Table 6-8 presents some of the desired properties for solar applications; Table 6-9 lists some potential candidates; and Table 6-10 summarizes some of the features of each. A detailed discussion of heat transfer fluids is beyond the scope of this section, but a discussion is presented in the Appendix for further review.

Table 6-8. DESIRED PROPERTIES

High Heat Capacity	Stable at Temperature = 350°F
Low Viscosity	Inexpensive
High Surface Tension	Non-toxic
Low Freezing Point	High Flash Point
Low Vapor Pressure	Dielectric
Non-corrosive	Non-scaling

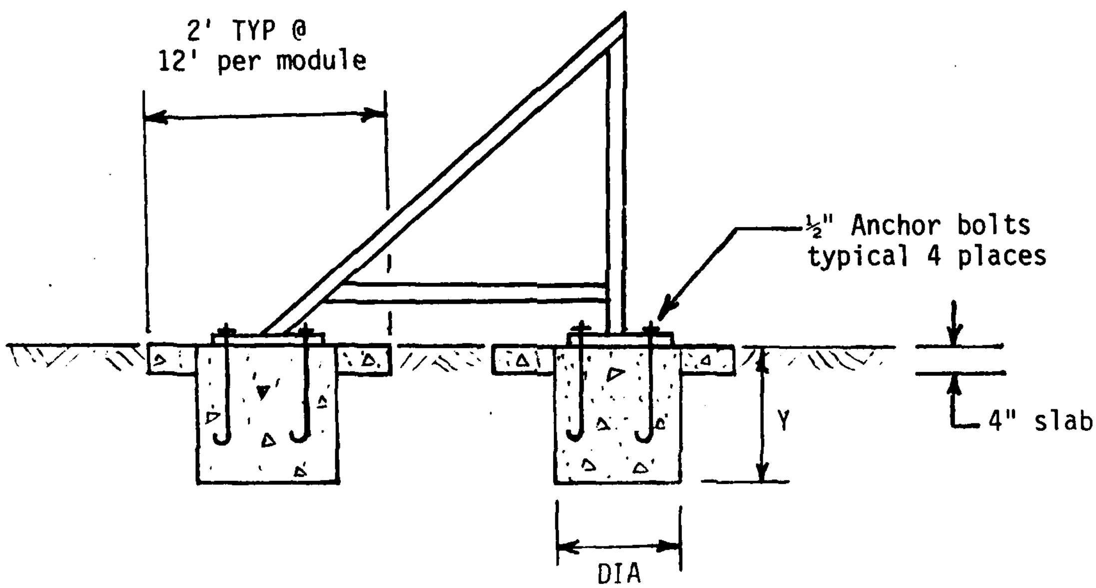


Figure 6-7. TYPICAL GROUND-MOUNTED COLLECTOR SUPPORT

Table 6-9. HEAT TRANSFER FLUIDS

Water	Petroleum Oils
Ethylene Glycol	Silicone Fluids
Propylene Glycols	Proprietory Fluids
Other Glycols	Fluoridated Hydrocarbons

For the present study, ethylene glycol/water solutions were selected as the heat transfer fluid because of their wide use in flat plate collectors. These common, colorless, odorless antifreeze solutions are also used in many other applications. Ethylene glycol is relatively inexpensive and available from many manufacturers. With corrosion inhibitors, aqueous ethylene glycol solutions can reduce the corrosive action and freezing temperature of water. These solutions are usually available in a wide range of concentrations and inhibitor levels. The thermal properties of the solutions (heat capacity, thermal conductivity, and viscosity) are poorer than those of water. Table 6-11 illustrates the increased flow rate - specific heat product as water. Table 6-12 illustrates the additional pressure drop resulting from the increased flow rate and viscosity.

Table 6-10. HEAT TRANSFER FLUIDS SUMMARY

	Disadvantages	Advantages
Water		
	• Freezes	• Excellent H.T. Medium
	• Requires Corrosion Inhibitors	• Cheap
	• Low Boiling Point	• Non-toxic
Glycol		
	• Forms Acid	• Good H.T. Medium
	• Requires Corrosion Inhibitors	• Relatively Inexpensive
	• Requires Periodic Maintenance	
	• Toxic	
	• Asphalt Solvent	
	• Low Boiling Point	
Hydrocarbon Oils		
	• Flammable	• High Boiling Point
	• Poor H.T. Fluid	• Low Toxicity
	• Relatively Inexpensive	
Silicone Oils		
	• Poor H.T. Fluid	• Stable
	• High Cost	• Non-corrosive
	• Low Surface Tension	• Low Toxicity

Table 6-11. INCREASED FLOW REQUIREMENT FOR SAME HEAT CONVEYANCE WITH 50% GLYCOL AS COMPARED WITH WATER

Fluid Temp. °F	Flow Increase Needed for 50% Glycol as Compared with Water
40	1.22
100	1.16
140	1.15
180	1.14
220	1.14

Source: "Solar Heating Systems Design Manual", ITT Fluid Handling Division, Bulletin TESE-576, Figure 4B, page 4-22.

Table 6-12. PRESSURE DROP CORRECTION FACTORS; 50% GLYCOL SOLUTION COMPARED WITH WATER

Fluid Temperature °F	Pressure Drop Correction Flow Rates Equal	Combined Pressure Drop Correction; 50% Glycol Flow Increased
40	1.45	2.14
100	1.1	1.49
140	1.0	1.32
180	.94	1.23
220	.9	1.18

Source: "Solar Heating Systems Design Manual", ITT Fluid Handling Division, Bulletin TESE-576, Figure 4-C, page 4-23.

The boiling and flash points of aqueous ethylene glycol mixtures are low and can be easily reached under zero flow conditions. Glycols can oxidize to organic acids (such as glycolic acids) when exposed to air near boiling temperatures. The inhibitors used are designed to neutralize these extremely corrosive acids. Periodic maintenance and addition of inhibitors must be done if these fluids are used. Many manufacturers provide a chemical analysis service to assure proper chemical balance. Another major drawback to the use of ethylene glycol is its high toxicity. Most plumbing codes require that ethylene glycol solutions be separated from potable water by double-walled heat exchangers. For the present application, toxicity will be a consideration only if the system is to be dumped to perform maintenance or if the glycol has undergone unacceptable deterioration due to excessive temperatures under no-flow conditions.

d. Active System Cost

Aboveground Storage: Detailed capital costs were estimated for the above active system for collector locations on the tank roof and on the ground. Collector areas were taken to be those resulting from the transient analysis. The following assumptions were applied:

- labor costs were determined from Means[7]
- factors were used to account for various labor rates between sites
- a 5% project management fee
- a 1½% design and engineering fee
- 10% escalation

Operation, maintenance, and replacement costs were not estimated. For the contractor markups the following assumptions were used:

- supervision 10%
- sales tax 4%
- payroll 17%
- overhead 10% (electrical) and 15% (mechanical)
- profit 10%

---

[7] "Mechanical and Electrical Cost Data 1979," Robert Snow Means Co., Inc.

Table 6-13 presents the complete capital cost per tank (1.25 MMB capacity) of the active heating system for roof-mounted arrays. Note that "system" includes insulation and heat exchanger. Table 6-14 presents the capital cost for arrays mounted on the ground. These numbers do not include the cost of additional land for siting the collectors and providing sufficient clearance between tanks to provide access to the sun. As a point of reference, the tank alone is estimated to cost about $5/bbl or about $6.25 million each. A complete steam heating plant, including pumps, distribution, and heat exchangers would cost approximately $6.70 per bbl, or $8.375 million for each 1.25 MMB tank.

Table 6-13. TOTAL SYSTEM COST FOR ABOVEGROUND STORAGE* (MM$ PER TANK)
- Roof-Mounted Systems -

Location	Product Temperature, °F			
	90	100	110	120
Portland, Maine	2.214	3.408	3.996	4.491
New York, New York	2.059	2.372	2.724	4.066
Norfolk, Virginia	1.324	1.540	1.778	2.062
Jacksonville, Florida	1.130	1.403	1.626	1.886

* Includes heat exchanger and tank insulation costs

Table 6-14. TOTAL SYSTEM COST FOR ABOVEGROUND STORAGE* (MM$ PER TANK)
- Ground-Mounted Systems -

Location	Product Temperature, °F			
	90	100	110	120
Portland, Maine	2.357	2.868	3.414	4.367
New York, New York	2.049	2.500	3.009	3.984
Norfolk, Virginia	1.553	1.865	2.210	2.619
Jacksonville, Florida	1.272	1.668	1.990	2.365

* Includes heat exchanger and tank insulation costs.

[7] Based on a 10 MMB farm, 800,000-bbl tank capacity. Personal Communications with Corps of Engineers, Huntsville Division

Since there is no additional cost of tank structure for roof-mounted arrays in Jacksonville and Norfolk, this approach has a definite advantage over ground-mounted arrays with the longer pipe runs. The opposite was true for New York and Portland because the additional tank costs at these sites overrode the cost of additional piping. The cost of land was not taken into account when estimating the costs of the ground-mounted system.

Table 6-15 illustrates costs of active solar systems for heating belowground cut-and-cover tanks of 1.25 MMB capacity. There is a definite capital cost advantage over aboveground storage, particularly at the northernmost locations. As a point of reference the cost of the conventional oil-fired system is $4.50 million for each tank.[7]

Table 6-15. TOTAL SYSTEM COST FOR BELOWGROUND CUT-AND-COVER STORAGE* (MM$ PER TANK)

Location	Product Temperature, °F			
	90	100	110	120
Portland, Maine	1.595	2.223	2.578	2.983
New York, New York	1.691	1.983	2.314	2.691
Norfolk, Virginia	1.428	1.568	1.791	2.061
Jacksonville, Florida	1.250	1.435	1.650	1.894

* Includes heat exchanger and insulation costs.

6.2 PASSIVE SYSTEMS

Passive systems are attractive solar heating concepts for long-term residual oil storage because the heat exchanger common to all other systems can be eliminated in many instances. In this section the passive concept found to have the greatest potential will be defined further.

a. System Description

The direct gain roof system is illustrated in Figure 6-8. The concept basically consists of a roof which is transparent to solar radiation. The radiation transmitted through this roof is intercepted by the top surface of the product and is consequently heated. Because the hotter, lighter fluid is located at the top of the mass, convective currents will not develop and a stirer may be required to assure uniformity of temperature. Since the heat lost from the product must be balanced by the net solar gain, the roof collector area is a strong function of local climatic conditions The method of analysis used to size the collector area, and collector area requirements for each site, is outlined in Section 7.2b.

[7] Ibid

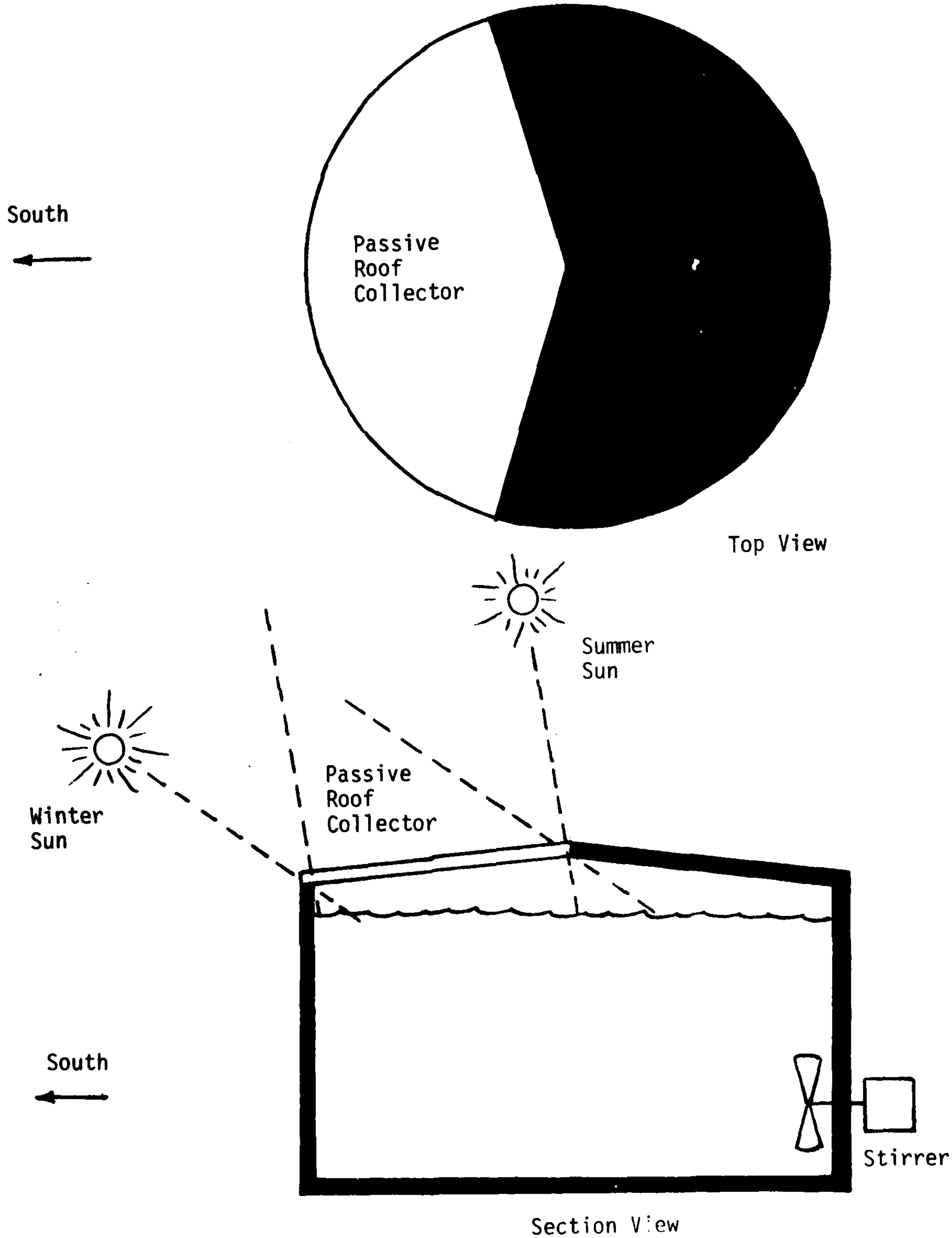


Figure 6-8. Passive Solar System

b. Collector Details

A number of products are being manufactured for the building industry which are potentially suitable for the present application. For this preliminary study a double-skinned acrylic sheet product of the CY/RO Industries was selected. The company also makes a similar sheet formed of polycarbonate which is stronger, but also more expensive and with a lower solar transmittance.

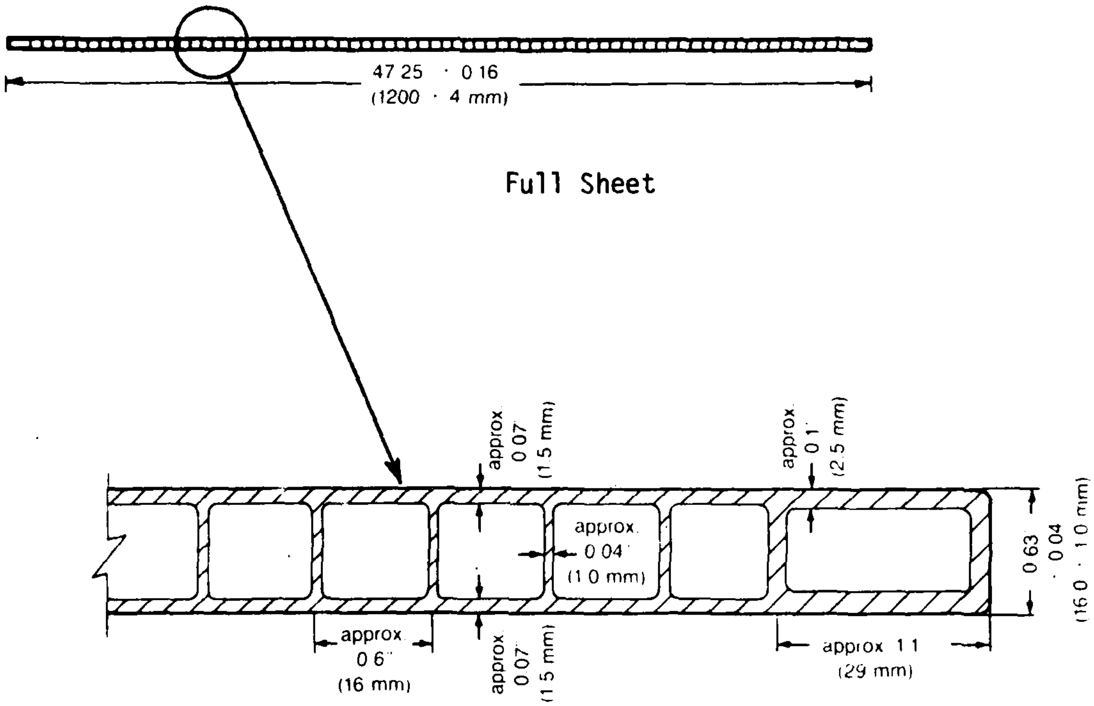
Figure 6-9 illustrates a cross-section of the EXOLITE sheet. It is a double layer, high light-transmitting glazing material with outstanding weatherability and excellent insulating characteristics. The product is designed for both sloped and vertical glazing in skylights, swimming pool enclosures, and industrial applications. The company also produces a line of extruded aluminum mullions which facilitates installation and provides extreme durability. Specifications are presented in Table 6-16.

EXOLITE sheet is produced from an acrylic molding compound which is a combustible thermoplastic. For this reason it would be unacceptable as a fuel oil tank material. Detailed studies were conducted using the material to indicate the potential for passive heating.

c. Structural Considerations

Figure 6-10 illustrates the EXOLITE panel mounting technique. The most important consideration in supporting the EXOLITE panels is the relatively small center spacing required. This will require additional purlins beyond that normally required for the 3/16" steel decking the panels will replace. Figure 6-11 illustrates the purlin spacing normally used in tank construction (solid lines) and those that must be added to support the flexible EXOLITE sheet (dashed lines).

In addition to purlins to support the dead load, wind forces will create an uplift of 35 psf requiring a hold down strap across the panel at a 56" spacing. Table 6-17 presents a summary of weights as impacted by the solar roof. The cost summary is shown in Table 6-18.



Full Sheet

Detail View

Figure 6-9. CROSS-SECTION OF EXOLITE ACRYLIC SHEET

Table 6-16. SPECIFICATIONS OF EXOLITE ACRYLIC SHEET

PHYSICAL PROPERTIES

Sheet thickness		0.63 in. ± 0.04 in. (16.0 mm ± 1.0 mm)
Width of Sheet		47.25 in. ± 0.16 in. (1200 mm ± 4 mm)
Lengths		8, 10, 12 and 16 feet (2.4, 3.0, 3.6, 4.8 m) other lengths available on request
Skin thickness	approx.	0.07 in. (1.5 mm)
Rib thickness	approx.	0.04 in (1.0 mm)
Distance between ribs	approx.	0.63 in. (16.0 mm)
Weight per unit area	approx.	1 lb sq. ft. (4.8 kg m²)
Heat transfer coefficient[1] (U)	summer conditions	0.55 BTU/hr./sq. ft./°F. (3.2 W/m²/°C)
	winter conditions	0.58 BTU/hr./sq. ft./°F (3.3 W/m²/°C.)
Coefficient of linear thermal expansion		40 x 10 ⁻⁶/°F. (70 x 10 ⁻⁶/°C.)
Maximum service temperature without load		160°F. (71°C.)

	Clear
Light Transmittance (ASTM D 1003)	83%
Solar Transmssion (ASTM E 424 —Method A)	83%
Shading Coefficient (ASHRAE Handbook)	0.97

Average sound reduction .... 23 dB

MECHANICAL PROPERTIES

Maximum bending moment relative to unit length		
Support perpendicular to ribs		290 ft. lbs./ft (1300 Nm/m)
Support parallel to ribs (supports spaced 45 in.) (Equal to 34.1 PSF)		120 ft. lbs./ft. (550 Nm/m)
Permissible bending moment relative to unit length		
Support perpendicular to ribs	roof glazing	31 ft. lbs./ft. (140 Nm/m)
	vertical glazing	62 ft. lbs./ft. (280 Nm/m)
Support parallel to ribs	roof glazing	13 ft. lbs./ft. (60 Nm/m)
	vertical glazing	26 ft. lbs./ft. (120 Nm/m)

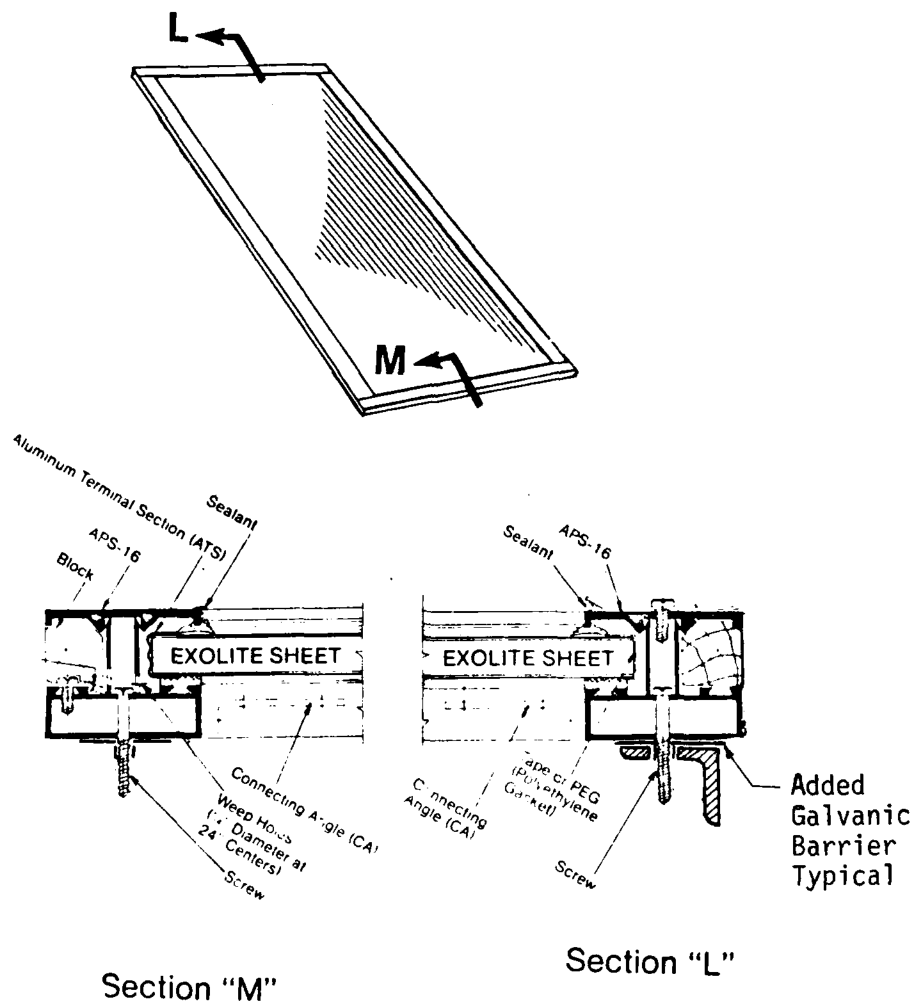


Figure 6-10. EXOLITE PANEL MOUNTING METHOD

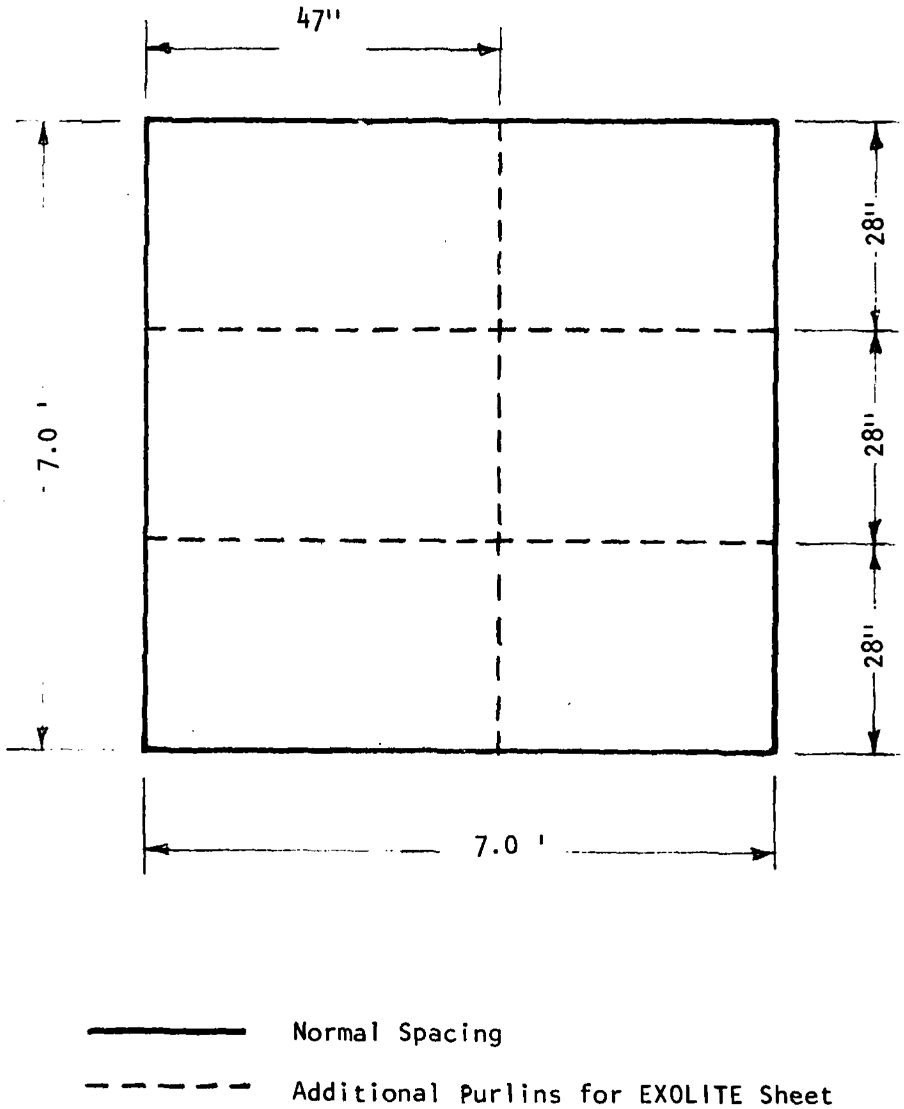


Figure 6-11. PURLIN SPACING FOR THE TANK ROOF

Table 6-17. SUMMARY OF NET WEIGHT DIFFERENTIALS

Weight Summary	psf
Remove Deck	- 0.77
Add Purlins	+ 1.10
Add Straps	+ 0.92
Net Weight psf	+ 1.25

Table 6-18. COST SUMMARY OF PASSIVE SOLAR SYSTEM

Location	Weight psf	Cost $/lb	Net Cost $/ft^2
Maine	1.25	1.50	1.88
New York	1.25	1.35	1.69
Virginia	1.25	1.20	1.50
Florida	1.25	1.08	1.35

d. Passive System Cost

Passive system capital costs were determined in some detail. Table 6-19 presents the results for the four sites and product temperatures considered. These costs are based on collector areas resulting from the transient analysis.

Table 6-19. DIRECT GAIN SYSTEM COST* (MM$ PER TANK)

	Product Temperature, °F			
Location	90	100	110	120
Portland, Maine	1.473	NF**	NF	NF
New York, New York	1.061	1.367	NF	NF
Norfolk, Virginia	0.950	1.068	1.447	NF
Jacksonville, Florida	0.878	0.939	1.032	1.205

* Includes cost of tank insulation
** Not feasible

The passive system obviously has a cost advantage over the active system in those instances in which it is thermodynamically viable.

6.3 HEAT PUMP SYSTEM

Only a cursory examination was given to detailing the heat pump design. Of the three solar heating concepts examined, the heat pump is the only one that has the potential for heating upon demand when the withdrawal of the product is required. In this sense it is quite similar to a conventional boiler heating system.

a. Heat Pump Schematic

Figure 6-12 illustrates a schematic of the heat pump system. It essentially produces heated water (or some other heat transfer fluid) just as an active solar system does. Since it is impractical to maintain the product continuously, the heat pump would be utilized only when product extraction is required. Since the specific heat pump unit considered for this study does not have adequate capacity to provide the energy rate necessary for extraction, a multiplicity of units will be required. These are shown in Section 7.2.

b. Heat Pump Performance

To evaluate the feasibility of heat pumps for heating residual oil, the characteristics of the Westinghouse Templifier were chosen as typical of those suitable for this application. The Templifier is an industrial heat pump capable of generating process heat up to 230°F using single- and two-stage centrifugal compressors. These systems are derived from those typically employed for air-conditioning large commercial, institutional, and industrial buildings. Sullair and Dunham-Bush have used the helical rotary screw compressor as the basic elements in waste heat recovery heat pump systems. These systems are primarily industrial refrigeration and air-conditioning applications and are noted for their long life and linear capacity feature.

Figure 6-13 illustrates the heating capacity of the TEMPLIFIER Model TPB-060A as a function of the leaving source water temperature and the leaving hot water temperature. The Coefficient of Performance, defined as

$$\frac{\text{energy in the leaving hot water}}{\text{energy required to operate compressor}}$$

is presented in Figure 6-14. Finally, the compressor power required to produce hot water is shown in Figure 6-15.

c. Heat Pump Costs

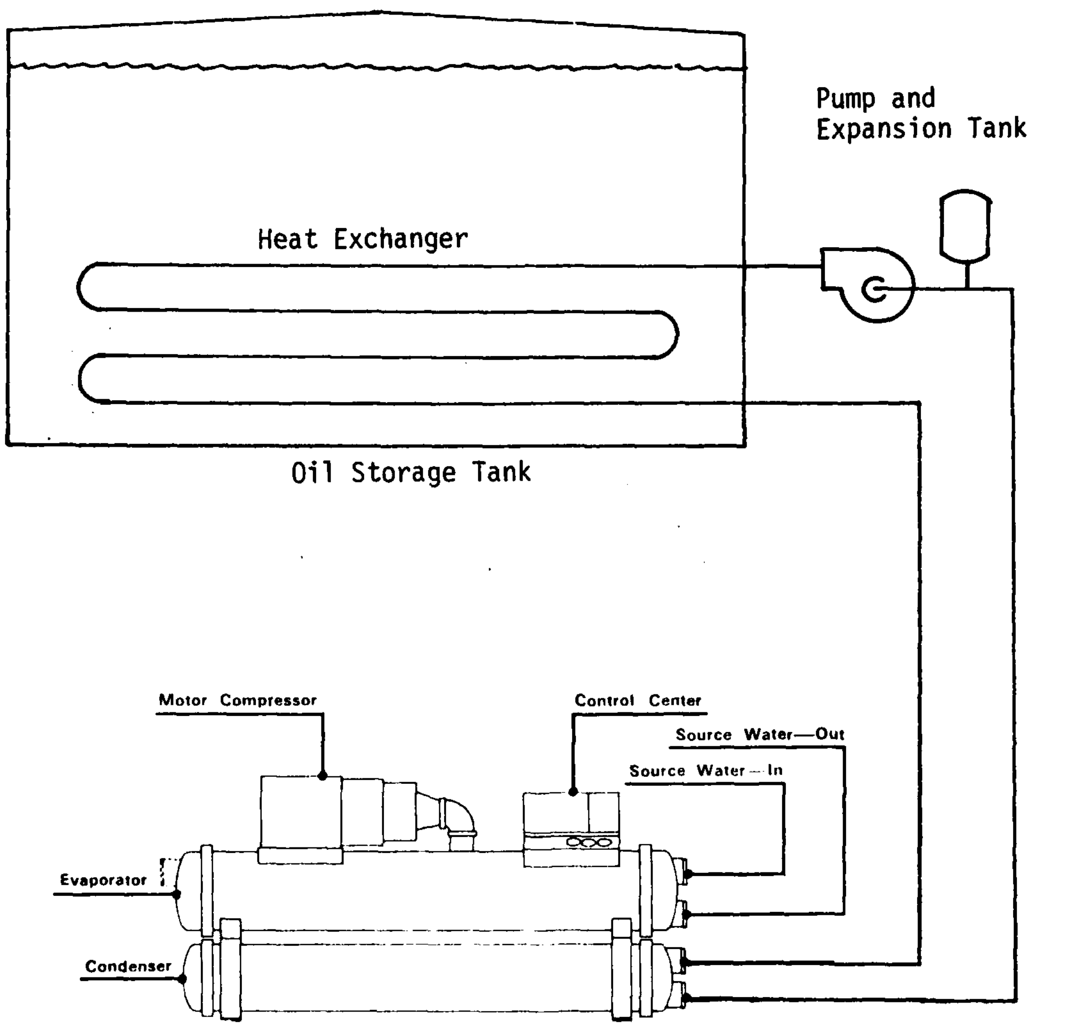
A detailed costing of the heat pump system was beyond the scope of this study; however, approximate values of installed cost are available. These are presented in Table 6-20 for various product extraction temperatures.

Table 6-20. HEAT PUMP INSTALLED COST PER TANK (1.25 MMB)

	Product Temperature, °F			
Extracted Time	90	100	110	120
45 days	\$300,000	\$400,000	\$600,000	\$850,000
60 days	\$200,000	\$350,000	\$500,000	\$650,000

To these costs must be added the costs of the water lines to the discharge of the power plant condenser, distribution system, heat exchangers, etc.

Tank insulation will not be required as with the continuous heating solar concepts.



Heat Pump (more than one required)

Figure 6-12. HEAT PUMP SYSTEM

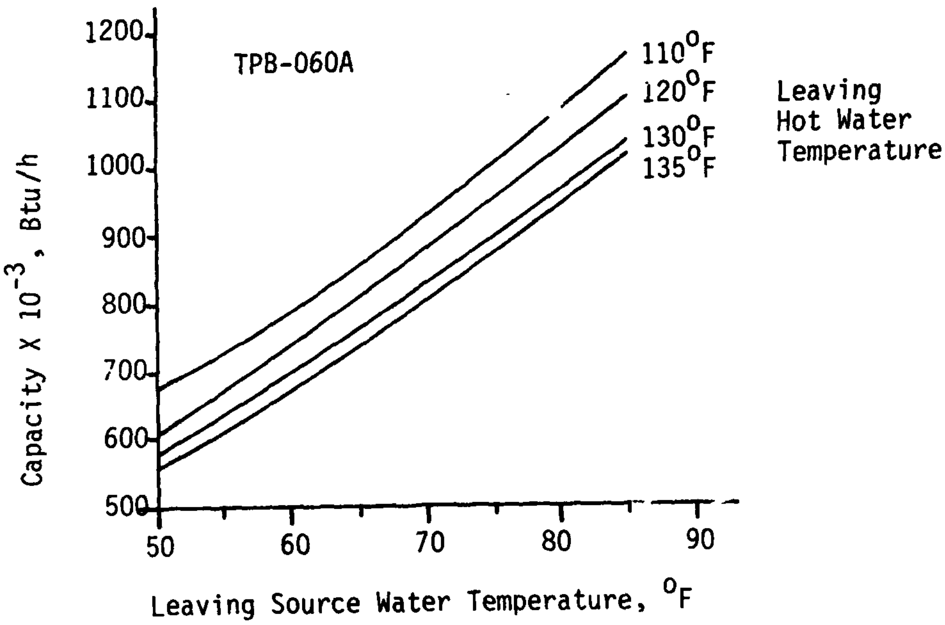


Figure 6-13. TEMPLIFIER HEAT PUMP PERFORMANCE

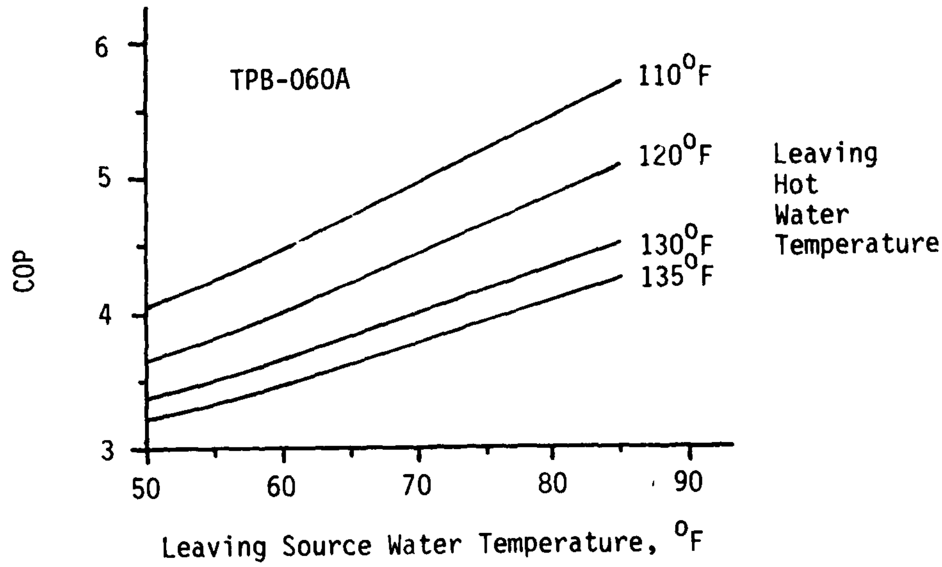


Figure 6-14. TEMPLIFIER HEAT PUMP PERFORMANCE

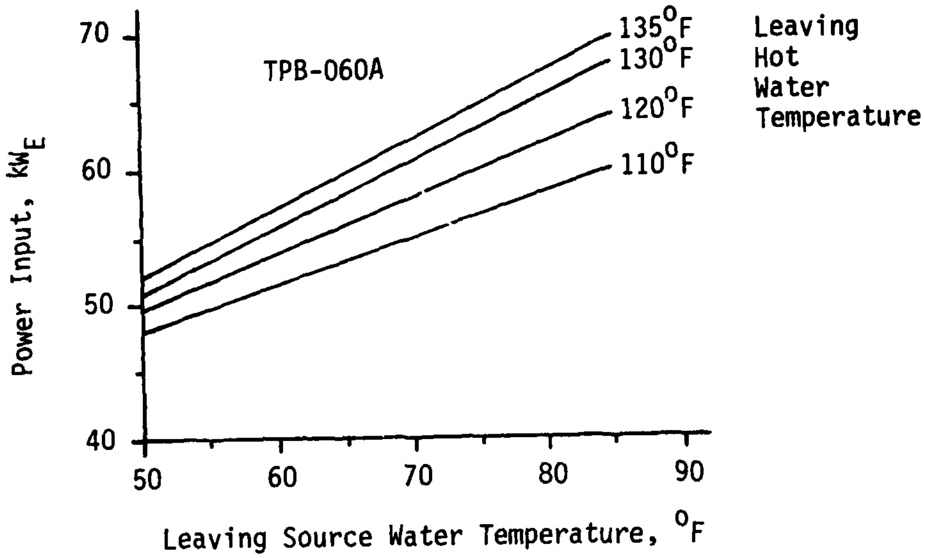


Figure 6-15. TEMPLIFIER HEAT PUMP PERFORMANCE

CHAPTER 7
SYSTEMS ANALYSIS

In this section, the important system technical and economic criteria will be defined and the methodology and analytical techniques employed will be described. The section first treats the all important thermal characteristics of the various storage systems considered in this study. Performance analysis were then conducted to identify system sizing criteria.

7.1 CONTAINER THERMAL CHARACTERISTICS

Because solar is best suited to maintaining a relatively stable temperature over the long period, the tank thermal characteristics, along with the environmental temperature, establish the heat loss and consequently, the solar collector size. The thermal characteristics of the three types of storage will be treated in the subsequent paragraphs.

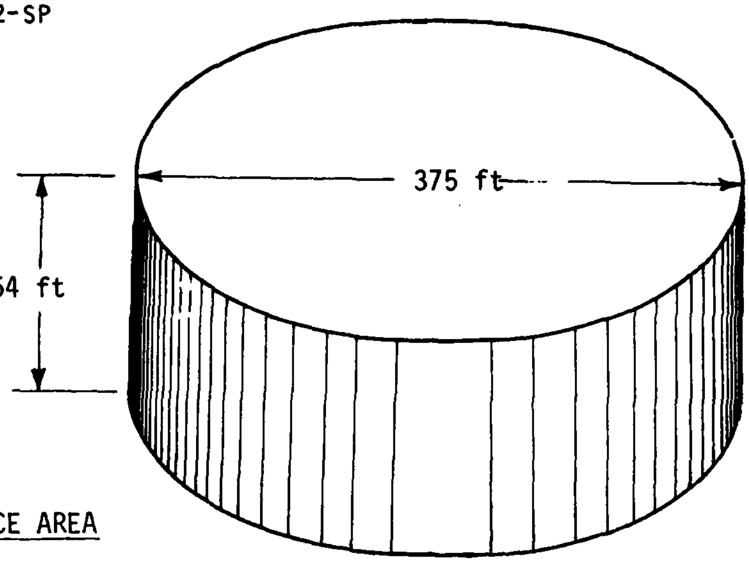
a. Aboveground Storage Thermal Characteristics

(1) Physical Characteristics: The aboveground storage tanks considered in this study are 375 ft. in diameter and 64 ft. high and contain 1,250,000 barrels of stored products. Figure 7-1 shows a typical tank along with the surface area of the walls, roof, and bottom. The tanks have a fixed, very slightly pitched conical roof which will shed water but will not seriously affect the design or installation of a solar heating system or of insulation.

(2) Seasonal Heat Loss: For a product storage at temperature above the ambient air temperature, the exposed surfaces of the tank walls, roof, and bottom constantly lose heat to the surroundings. The walls and roof lose heat directly to the ambient air. The tank bottom loses heat indirectly to the ambient air through the soil at the tank edges and to the deep ground at the center of the tank bottom. Figure 7-2 shows the temperature and heat losses from the various parts of the tank. The total heat loss Q_T from the tank is the sum of the heat losses from the exposed tank parts.

On an annual basis, the product is stored at an average temperature ($\overline{T}$) and an average annual ambient air temperature of $\overline{T}_a$ giving an annual average temperature difference ($\overline{T} - \overline{T}_a$) that produces the heat losses from the tank to the air.

The tank bottom loses heat to the ambient air through the soil at the edges, Q_E, and to the deep ground from the center of the tank bottom. The average annual deep ground temperature is equal to the average



SURFACE AREA

Top	110,447	ft^2
Bottom	110,447	ft^2
Walls	75,398	ft^2
Total Top & Walls	185,845	ft^2
Total Top & Walls & Bottom	296,292	ft^2
Volume	52,880,072	gal
"	1,259,054	bbl
Perimeter	1,178	ft

Figure 7-1. STORAGE TANK PHYSICAL CHARACTERISTICS

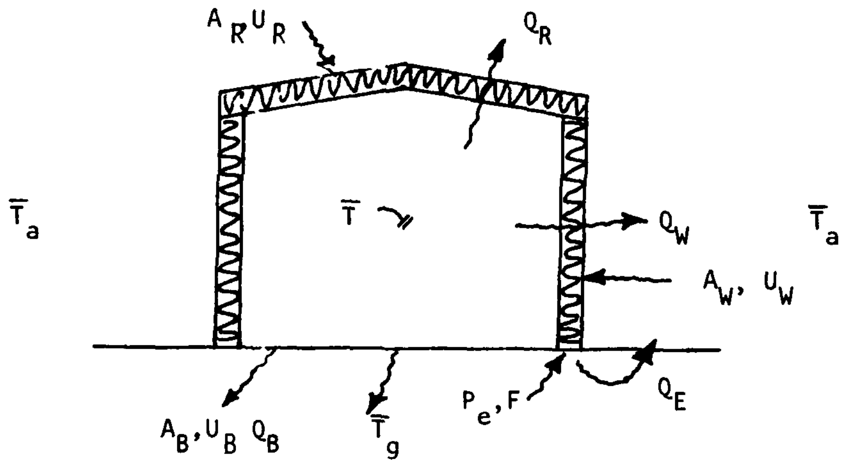


Figure 7-2. TANK HEAT LOSS

annual air temperature; so the annual heat loss from all elements of the tank are based on a heat sink whose temperature is equal to the average annual air temperature T_a.

The heat losses from an uninsulated tank can be calculated using Equation 7-1. Without insulation there is little resistance to heat flow and the heat transfer coefficients U will be due to the surface convection heat transfer resistance on the inside and outside of the tank. The heat transfer coefficients for an uninsulated tank are given in Table 7-1. The daily total overall heat loss coefficient is given by

$$\text{DAILY TOTAL } U_oA_o = 403{,}410 \frac{\text{Btu}}{\text{hr}^\circ\text{F}} \times 24 \frac{\text{hr}}{\text{day}} = 9.682 \times 10^6 \frac{\text{Btu}}{\text{day}^\circ\text{F}} \qquad (7\text{-}1)$$

The average daily heat loss is given by the product of the overall heat loss coefficient and the temperature difference.

$$Q_{DAILY} = U_oA_o \ (\overline{T} - \overline{T}_a) \quad \text{Btu/day} \qquad (7\text{-}2)$$

$$= 9.682 \times 10^6 \frac{\text{Btu}}{\text{day}^\circ\text{F}} (\overline{T} - \overline{T}_a) \quad \text{Btu/day}$$

Then for a specific average product temperature $\overline{T}$ and ambient air temperature $\overline{T}_a$ at a particular location, the average heat losses can be calculated using Equation 7-2.

When insulation is added to the tanks roof and walls, the resistance to heat transfer increases and that surfaces heat transfer coefficient, U, is decreased, and the overall heat loss coefficient decreases. Table 7-2 gives the overall heat loss coefficients, UA, for the various exposed tank surfaces for polyurethane foam insulation at thicknesses from 0 to 3 inches. Due to the ease of installing the foam insulation and

Table 7-1. UNINSULATED TANK HEAT LOSS COEFFICIENTS

Tank Surface	Variable	Heat Transfer Coefficient Btu/hr ft^2 °F	Area ft^2	Overall Heat Transfer Coefficient Btu/hr °F
Walls	U_W	3.39	75,398	255,599
Roof	U_R	1.30	110,447	143,544
Perimeter	F	0.81	1,178	954
Bottom	U_B	0.03	110,447	3,313
TOTAL U_oA_o				403,410

low cost estimates, polyurethane foam seems to be the preferred insulation for these large storage tanks. It is considered as the insulating material throughout this study. The overall tank heat loss is shown in Figure 7-3 along with the approximate cost of the insulation. Tables 7-3a, b, c, and d provide values of the seasonal heat load for the various sites and product temperatures under consideration.

The evolution of an optimum solar energy system involves simultaneously optimizing the collector size along with the tank insulation thickness. Figure 7-4 illustrates the cost of the solar system alone (assuming \$25/ft^2 system cost), the insulation cost and the sum of the two costs. The optimum balance between collector cost and insulation cost is achieved if the total cost is a minimum. This generally occurs at all the locations considered when about 3 inches of insulation is used at a product temperature of 120°F, and 2 inches at a temperature of 90°F. Considerating all the sites, the optimum insulation thickness of 3 inches was used as a basis for studies conducted in this report.

$$Q_T = UA_o\ (T - \overline{T}_a) = Q_R + Q_W + Q_E + Q_B$$

$$= U_R A_R (T - \overline{T}_a) + U_W A_W (T - \overline{T}_a) + F\ P_e\ (T - \overline{T}_a)$$

$$+ U_B A_B (\overline{T} - \overline{T}_g)$$

$$= U_R A_R + U_W A_W + F\ P_E + U_B A_B \quad X\ (\overline{T} - \overline{T}_a)$$

where:

Q_T = Total Average Tank Heat Loss (Btu/hr)

T = Average Annual Temperature ($^{\circ}$F)

$\overline{T}_a$ = Average Annual Ambient Air Temperature ($^{\circ}$F)

$\overline{T}_g$ = Average Annual Ground Temperature = $\overline{T}_a$ ($^{\circ}$F)

U_R = Roof Heat Loss Coefficient (Btu/hr ft^2°F)

U_W = Wall Heat Loss Coefficient (Btu/hr ft^2°F)

A_R = Roof Surface Area = $\pi D^2/4$ (ft^2)

A_W = Wall Surface Area - πDH (ft^2)

P_e = Tank Bottom Edge Perimeter Length - πD (ft)

F = Perimeter Heat Loss Coefficient (Btu/ft hr$^{\circ}$F)

Q_R = Roof Total Heat Loss (Btu/hr) Q_E = Edge Heat Loss (Btu/hr)

Q_W = Wall Total Heat Loss (Btu/hr) Q_B = Bottom Heat Loss (Btu/hr)

A_B = Bottom Surface Area = $\pi D^2/4$ (ft^2)

U_B = Bottom Heat Loss Coefficient (Btu/hr ft^2°F)

Table 7-2. INSULATED TANK OVERALL HEAT LOSS COEFFICIENT

Insulation Thickness	Wall $U_W A_W$	Roof $U_R A_R$	Perimeter FP_E	Bottom $U_B A_B$	TOTAL $U_0 A_0$ Hourly	Daily
Inches	Btu/hr°F	Btu/hr°F	Btu/hr°F	Btu/hr°F	Btu/hr°F	10^6 Btu/day°F
0	255,599	143,544	954	3313	403,410	9.682
¼"	37,605	43,245	954	3313	85,117	2.043
½"	19,883	25,454	954	3313	49,604	1.190
1"	10,242	13,965	954	3313	28,474	0.683
1½"	6,897	9,622	954	3313	20,786	0.4989
2"	5,199	7,339	954	3313	16,805	0.403
2½"	4,172	5,932	954	3313	14,371	0.345
3"	3,484	4,976	954	3313	12,727	0.305

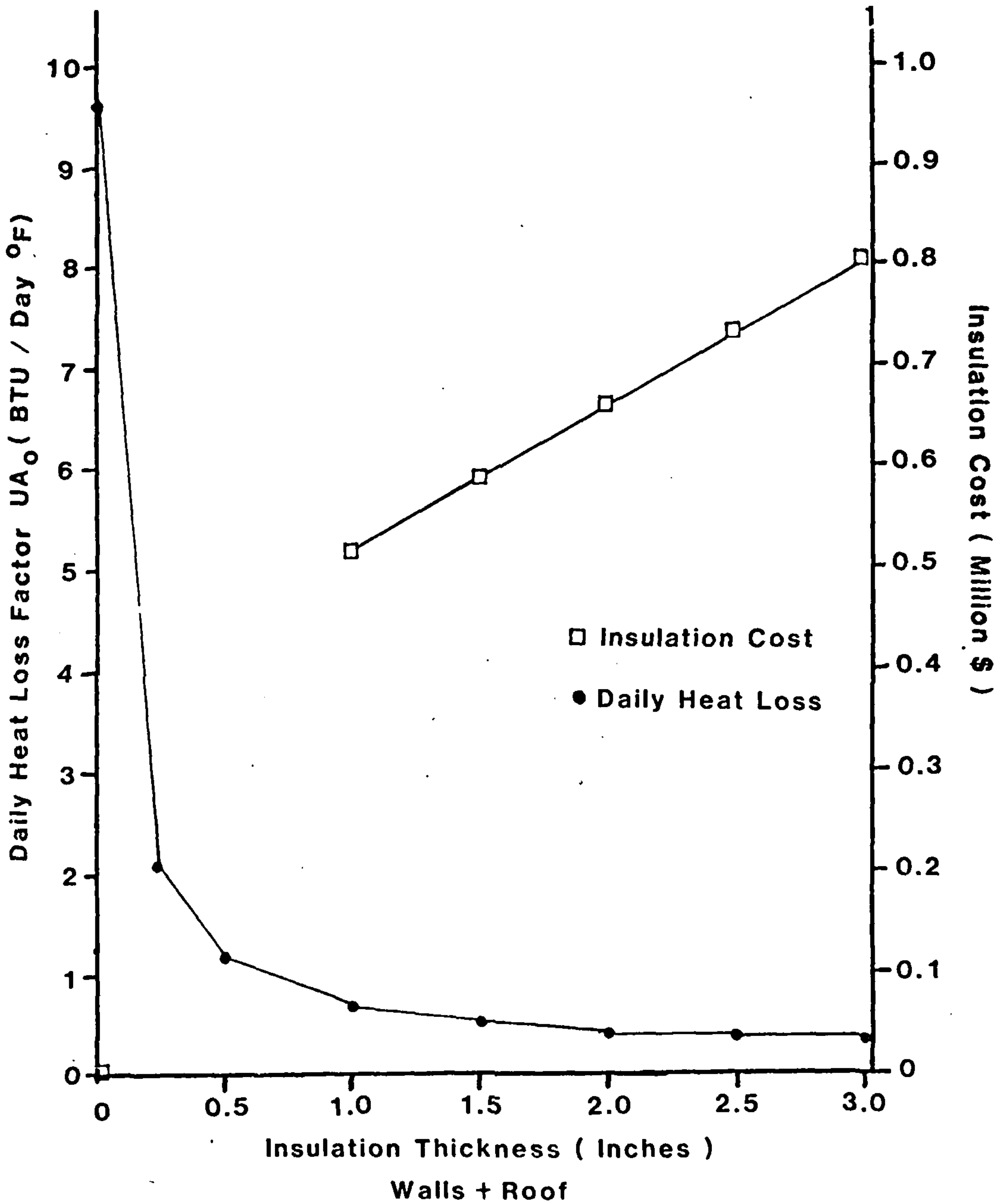


Figure 7-3. TANK HEAT LOSS AND INSULATION COST

Table 7-3a
TANK HEAT LOSS

LOCATION: Portland, Maine
$\overline{T}_a = 45.0^{o}F$

Insulation Thickness	Daily Heat Loss Factor UA_o	Annual Heat Loss Factor UA_o	PRODUCT TEMPERATURE, ^{o}F			
			90	100	110	120
Inches	10^6Btu/DAY^{o}F	10^6Btu/YR^{o}F	10^6Btu/YR	10^6Btu/YR	10^6Btu/YR	10^6Btu/YR
0	9.682	3533.9		194,365	229,704	265,043
0.25	2.043	745.7		41,014	48,471	55,928
0.5	1.190	434.4		23,892	28,236	32,580
1.0	0.683	249.3		13,712	16,205	18,698
1.5	0.499	182.1		10,016	11,837	13,658
2.0	0.403	147.1		8,091	9,562	11,033
2.5	0.345	125.9		6.925	8,184	9,443
3.0	0.305	111.3	5,009	6,122	7,235	8,348
TEMPERATURE DIFFERENCE (^{o}F) ($\overline{T}_{bulk} - \overline{T}_{AMB}$)			45.0	55.0	65.0	75.0

Table 7-3b
TANK HEAT LOSS

LOCATION: New York, New York
$\overline{T}_a = 54.75^oF$

Insulation Thickness	Daily Heat Loss Factor UA_o	Annual Heat Loss Factor UA_o	PRODUCT TEMPERATURE, ^oF			
			90	100	110	120
Inches	10^6Btu/DAY^oF	10^6Btu/YR^oF	10^6Btu/YR	10^6Btu/YR	10^6Btu/YR	10^6Btu/YR
0	9.682	3533.9				
0.25	2.043	745.7				
0.5	1.190	434.4				
1.0	0.683	249.3				
1.5	0.499	182.1				
2.0	0.403	147.1				
2.5	0.345	125.9				
3.0	0.305	11.3	3,923	5,036	6,149	7,262
TEMPERATURE DIFFERENCE (^oF) ($\overline{T}_{bulk} - \overline{T}_{AMB}$)			35.25	45.25	55.25	65.25

Table 7-3c
TANK HEAT LOSS

LOCATION: Norfolk, Virginia
$\overline{T}_a = 59.92^oF$

Insulation Thickness	Daily Heat Loss Factor UA_o	Annual Heat Loss Factor UA_o	PRODUCT TEMPERATURE, ^oF			
			90	100	110	120
Inches	10^6Btu/DAY^{o}F	10^6Btu/YR^{o}F	10^6Btu/YR	10^6Btu/YR	10^6Btu/YR	10^6Btu/YR
0	9.682	3533.9				
0.25	2.043	745.7				
0.5	1.190	434.4				
1.0	0.683	249.3				
1.5	0.499	182.1				
2.0	0.403	147.1				
2.5	0.345	125.9				
3.0	0.305	11.3	3,348	4,461	5,574	6,687
TEMPERATURE DIFFERENCE (^oF) ($\overline{T}_{bulk} - \overline{T}_{AMB}$)			30.08	40.08	50.08	60.08

Table 7-3d
TANK HEAT LOSS

LOCATION: Jacksonville, Florida
$\overline{T}_a = 65.6^{\circ}F$

Insulation Thickness	Daily Heat* Loss Factor UA_o	Annual Heat* Loss Factor UA_o	PRODUCT TEMPERATURE, °F			
			90	100	110	120
Inches	10^6Btu/DAY°F	10^6Btu/YR°F	10^6Btu/YR	10^6Btu/YR	10^6Btu/YR	10^6Btu/YR
0	9.682	3533.9	86,227	121,566	156,905	192,244
0.25	2.043	745.7	18,195	25,652	33,109	40,566
0.5	1.190	434.4	10,599	14,943	19,287	23,631
1.0	0.683	249.3	6,083	8,576	11,157	13,562
1.5	0.499	182.1	4,443	6,264	8,085	9,906
2.0	0.403	147.1	3,589	5,060	6,531	8,002
2.5	0.345	125.9	3,072	4,331	5,590	6,849
3.0	0.305	111.3	2,716	3,829	4,942	6,055
TEMPERATURE DIFFERENCE (°F) ($\overline{T}_{bulk} - \overline{T}_{AMB}$)			24.4	34.4	44.4	54.4

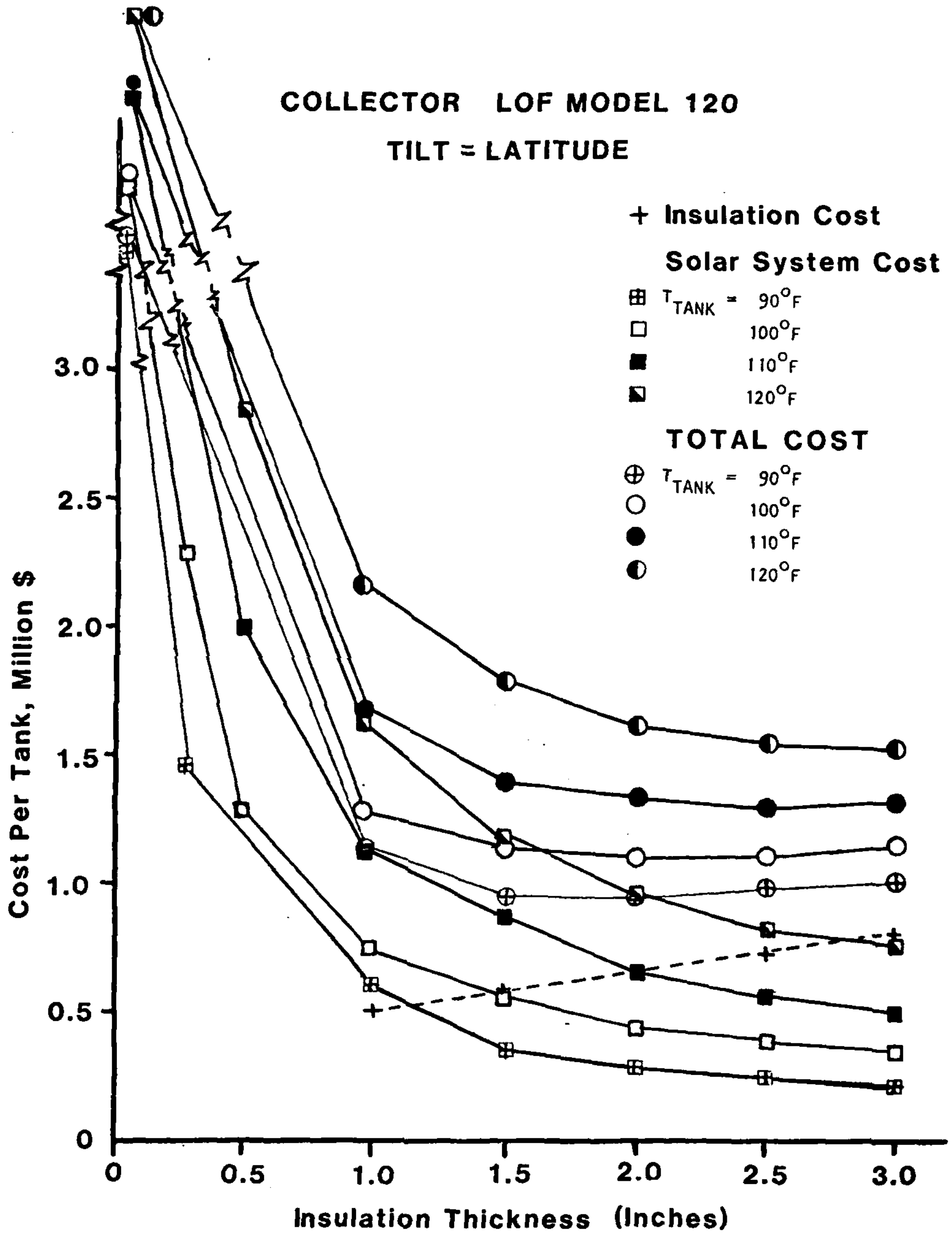


Figure 7-4. INSULATION & SOLAR SYSTEM COST, JACKSONVILLE FLORIDA

b. Belowground Storage Thermal Characteristics

When a tank is installed below ground, the heat loss from the tank flows to the surrounding earth which is a very large heat sink that changes temperature very slowly. The earth also acts as an insulator (near the tank) as well as a thermal storage medium. Due to the transient nature of the heat flows from the tank to the earth, and the three dimensional aspects of the tank's shape, the heat losses are difficult to calculate with simple steady-state heat transfer relationships. For these reasons several heat loss calculations methods for underground heated tanks were reviewed.

For applicability to the present problem the heat losses were found to be strongly affected by tank depth, tank radius, thermal resistance of tank insulation, thermal capacity of the earth, elevation of the water table, and ground surface heat transfer coefficient.[8] Also it was found that an overall heat transfer coefficient can be developed for a particular tank shape and soil conditions using a computer modeling technique.[9] These methods were validated using an underground storage tank for heating and cooling a house.[10] Because these methods require site specific data which were not available, and require considerable computer calculations, a complete transient analysis was not undertaken in this study. Instead an example of a very large underground heat storage tank was found for which a transient analysis had previously been performed.[11] Therefore, the insulation thickness and location and depth of fill used in this analysis were assumed for the underground tank cases. A heat loss coefficient, U, was found to be approximately 0.66 Btu/day ft^2°F and was assumed to approximate that of the 1,250,000-barrel storage tank. Figure 7-5 shows the heat losses in the underground tank, along with the thermal conductivity and thickness of the insulation used in this study. The heat losses from the belowground tank are given in Equation 7-3.

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[8] "A Design Method to Determine the Optimal Distribution and Amount of Insulation for Inground Heat Storage Tanks;" G.T. Williams, C.R. Attwater, F.C. Hooper; Dept. of Mechanical Engineering, University of Toronto

[9] "A Design Method for Heat Loss Calculation for Inground Heat Storage Tanks," F.C. Hooper and C.R. Attwater; Dept. of Mechanical Engineering, University of Toronto.

[10] "Annual Cycle Storage for Building Heating," F.C. Hooper

[11] "Solar Space Heating Systems Using Annual Heat Storage, Progress Report," Jan. 1-Sept. 30, 1978; F.C. Hooper, C.R. Attwater, A.P. Brunger, et.al., Department of Mechanical Engineering, University of Toronto.

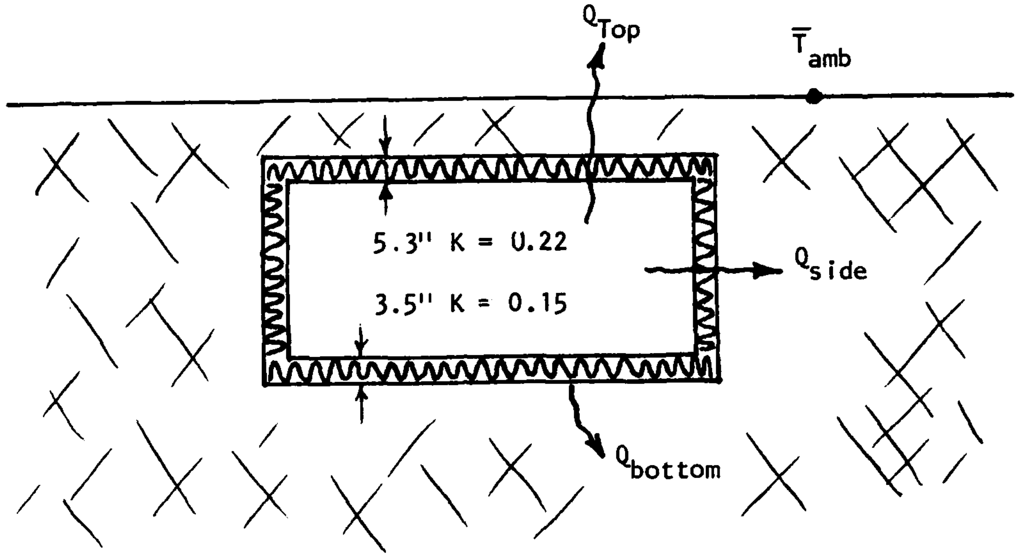

Figure 7-5. BELOWGROUND TANK HEAT LOSSES

Overall Heat Loss = $Q = UA(\overline{T}_{TANK} - \overline{T}_{amb})$ X 365 day/yr X 24 hr/day

U = overall tank heat loss coefficient (Btu/day ft^2 $^\circ$F)
A = tank outside surface area (ft^2)
$\overline{T}_{TANK}$ = annual average tank temperature ($^\circ$F)
$\overline{T}_{amb}$ = annual average ambient air temperature ($^\circ$F)

for insulation shown above

$$U \simeq 0.66 \text{ Btu/day ft}^{2\,\circ}\text{F}$$

$$A = A_{top} + A_{sides} + A_{bottom}$$
$$= 110{,}447 \text{ ft}^2 + 75{,}398 \text{ ft}^2 + 110{,}447 \text{ ft}^2$$
$$= \underline{\underline{296{,}292 \text{ ft}^2}} \simeq \underline{\underline{300{,}000 \text{ ft}^2}}$$

$$Q = (0.66 \text{ Btu/hr ft}^{2\,\circ}\text{F}) \ (300{,}000 \text{ ft}^2) \ (\overline{T}_{TANK} - \overline{T}_{amb}) \times 365 \text{ day/yr}$$

$$Q_{annual} = 72.7 \times 10^6 \ (\overline{T}_{TANK} - \overline{T}_{amb}) \quad \{\text{Btu/yr}\} \qquad (7\text{-}3)$$

On a long-term basis the average annual deep ground temperature is equal to the average annual air temperature. So, as in the case of the aboveground tank, the temperature difference driving heat flow is the average product temperature $\overline{T}$ minus the average air temperature $\overline{T}_a$. For

each location and product temperature Table 7-4 gives the annual heat load for a 1,250,000-barrel belowground tank.

c. Mine Thermal Characteristics

In a mined cavern, heat is lost from the storage to the surrounding rock, and through the leakage water that is continually pumped out of the mine. The magnitude of the heat losses is strongly dependent on the rate of water leakage into the cavern. For the purpose of this evaluation, heat losses from mined storage were based on a review of 75 existing operating mined storage containers[12] storing viscous fuel oils at temperatures between 120°F and 140°F. The average long-term heat losses resulting from conduction, water leakage and ventilation, and equipment are listed in Table 7-5 along with range of values found.

Table 7-4. BELOWGROUND TANK HEAT LOSS ($X10^6$ Btu/yr.)

LOCATION	AVG. ANNUAL TEMPERATURE $\overline{T}_{AMB}$ (^oF)	Tank Bulk Temperature Annual Average			
		90^oF	100^oF	110^oF	120^oF
Portland, Me.	45.03	3269	3996	4723	5450
New York, N.Y.	54.75	2563	3290	4017	4744
Norfolk, Va.	59.92	2187	2914	3641	4368
Jacksonville, Fl.	65.59	1774.6	2502	3229	3956

Table 7-5. MINED STORAGE HEAT LOSSES
(Btu/barrel/year)

	Range	Average
Conduction	5,200	5,200
Water Leakage	2,000-10,000	6,000
Ventilation, Piping & Equip.	500-1,000	750
TOTAL		11,950 Btu/bbl/yr

For a 1,250,000-barrel storage facility the annual heat losses are:

$$Q = 1,250,000 \text{ bbl} \times 11,950 \text{ Btu/bbl/yr} = \underline{14938 \times 10^6 \text{ Btu/yr}}$$

[12] "Management and Operating Cost of Underground Oil Storage," P. Nissiner, Rintekno, OY, Finland.

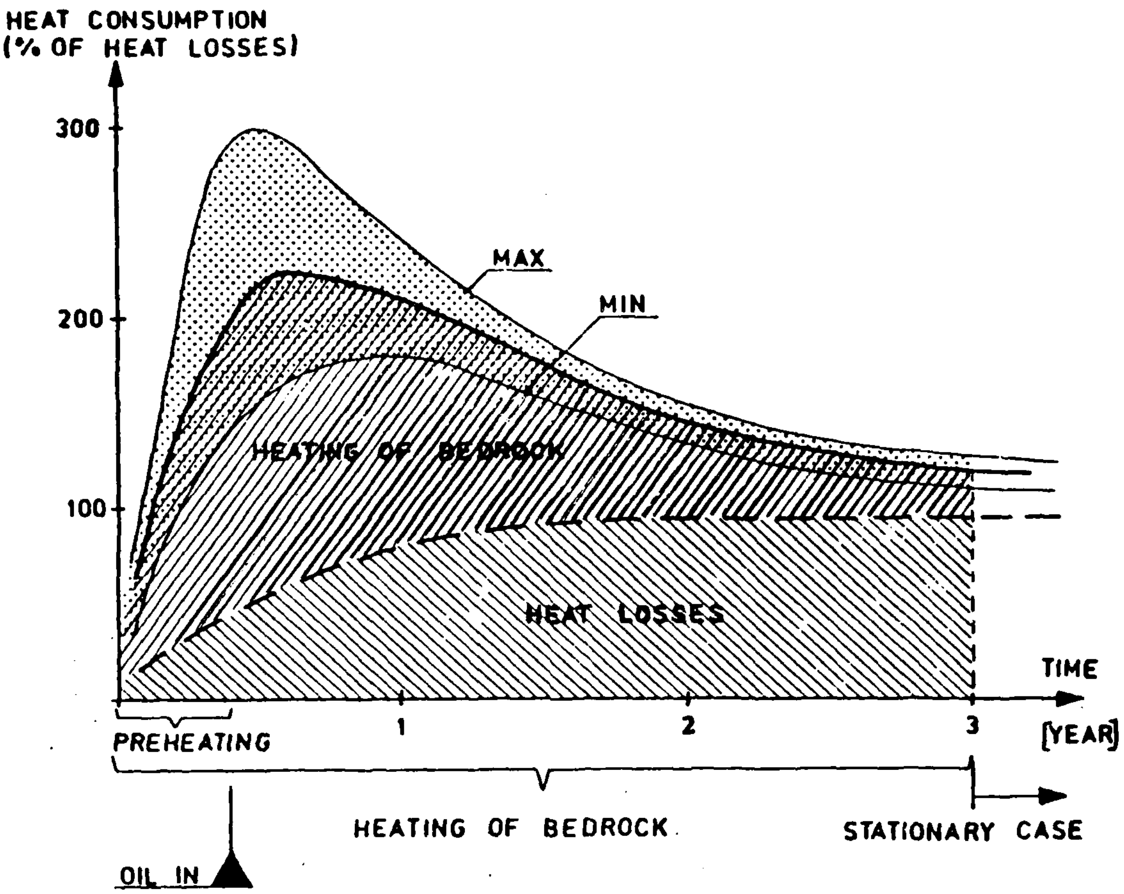

Figure 7-6. HEAT CONSUMPTION OF HEAVY FUEL OIL ROCK STORAGE

A storage cavern to store a heated product requires a significant warm up of the rock before the product is loaded. This warm-up energy requirement is estimated to be 20,000 - 30,000 Btu/barrel. A 1,250,000-barrel storage would require 25,000 - 37,500 X 10^6 Btu to preheat the cavern. The initial mine preheating and long-term heat losses are shown in Figure 7-6.

7.2 SYSTEM PERFORMANCE ANALYSES

In this section the results of the performance analyses, in terms of system size, will be provided. These results are preceded by a description of the analysis methods used.

a. Description of Analysis Methods

To analyze solar collector area requirements, two methods were employed. The first, a steady-state analysis was used to explicitly relate collector area to the long-term average temperature of the fluid. This approach facilitated rapid determination of a wide variety of design parameters. The second, a transient analysis, was developed primarily to determine the annual swings in average product temperature. Refined values of collector area were determined by trial-and-error, using successive choices of collector area as an independent parameter.

Steady-State Procedure: A heat balance on the storage tank results in the following relationship.

$$q_{in} - q_{out} = m\, c_p \frac{dT}{dt} \qquad (7\text{-}4)$$

where

q_{in} - heat into product

q_{out} - storage tank heat loss

m - mass of product stored

c_p - specific heat of product

T - bulk temperature of product

t - time

and it is implicitly assumed that the product is well stirred so that its temperature is relatively uniform.

Now if heat is supplied by a solar collector, then

$$q_{in} = A_c\, I\, \eta \qquad (7\text{-}5)$$

where

A_c - collector

I - total insolation incident on collector

η - collector efficiency

Equation 7-4 becomes

$$A_c\ I\ \eta - q_{out} = m\ c_p \frac{dt}{dt} \qquad (7\text{-}6)$$

which must be solved to determine variations of bulk temperature with time. For a first order evaluation of solar feasibility, this variation is assumed negligible over the long term. Thus on an annual basis

$$12\ A_c\ \bar{I}\ \eta - 365 \times 24\ \bar{q}_{out} = 0 \qquad (7\text{-}7)$$

where the $(\bar{\ })$ indicates annual averages.

Therefore,

$$A_c = \frac{365 \times 24\ \bar{q}_{out}}{12\ \bar{I}\ \eta} \qquad (7\text{-}8)$$

or

$$A_c = \frac{Q_{out}}{0.95 \sum_{n=1}^{12} (I_n)\eta} \qquad (7\text{-}9)$$

where

Q_{out} - heat loss per year

(I_n) - energy incident per month, n, per unit collector area

and the 0.95 factor accounts for heat loss in the piping, etc.

Solar radiation, I, has been presented in Chapter 3 for the four sites under consideration. Collector efficiency was calculated by a technique developed at NASA's Marshall Space Flight Center. Their relationship for efficiency is

$$\eta = F_R(\tau\alpha) - F_R U_L \frac{T - \bar{T}_{am}}{0.7\ I_m\ \ CF} \qquad (7\text{-}10)$$

where

$F_R(\tau\alpha)$, $F_R U_L$ = collector efficiency parameters

I_m = maximum clear day radiation, Btu/day ft^2

CF = clearness factor from Figure 3-13

where the average ambient temperature, $\bar{T}_{am}$, is the average of the normal maximum and normal minimum temperatures from Chapter 3.

Transient Procedure: For the transient analysis, the basic heat balance Equation 7-4 was written as

$$m\, c_p \frac{dt}{dt} = 0.95\ A_c F_R (\tau\alpha)\ I - 0.95\ A_c F_R U_L I_{(t)} \frac{(T - \bar{T}_{am})}{0.7\ I_m\ CF} - A_T U_T (T - T_{av}) \quad (7\text{-}11)$$

where

T_{av} = normal average temperature for the month

A computer program was developed to integrate Equation 7-11 using the trapezoidal rule.

b. Active System Collector Requirements

Aboveground Storage: Using the steady-state analysis procedure described in paragraph 7-2a, the collector areas were derived for each of the four sites. These results for aboveground tanks employing 3 inches of insulation are shown in Figure 7-7a-d. The High Performance collector refers to the LOF model 121 collector described in paragraph 6-1b and the Low Performance collector to the Model 120.

Optimum land use and reduced site work can be achieved if the collectors can be mounted on the tank roof. Figures 7-8a-d illustrate a plan view of the collector array and tank for the four sites under consideration. Subsequent cost studies indicated the high performance collector to be the most cost-effective; therefore, the array size was based upon this design.

All results in Figure 7-7 and Figure 7-8 were obtained with the collector tilted at the latitude of the site. Frequently, the annual collection efficiency can be improved by increasing the tilt slightly to compensate for poorer weather conditions in the winter. Figure 7-9 illustrates the collector area requirements for Jacksonville for two different tilt angles, e.g., tilt angle equal at the latitude and tilt angle equal the latitude plus 15°. Clearly, there was a deterioration in performance when the collector was tilted past the latitude angle. Therefore, this tilt was considered to be optimum for heating oil storage tanks.

Belowground Storage: Collector areas for the underground tanks are shown in Figures 7-10a-d. Cost studies, which will be described in paragraph 7.3, indicate the High Performance (e.g., the LOF Model 121 using a selective surface) to be the most cost-effective unit. Therefore, only this collector was used for these analyses.

Mined Storage: Collector areas for mined caverns were computed for one location, Portland, Maine. Figure 7-11 compares these computations with those of aboveground and belowground storage. The mined storage appears to be unsuitable for solar heating because of the large heat loads involved.

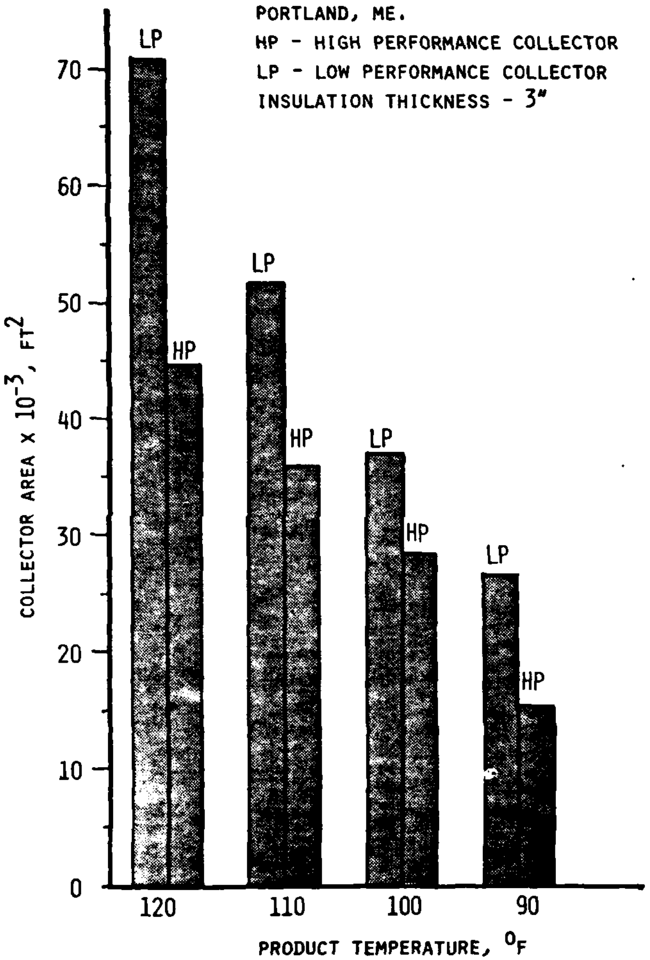

Figure 7-7a. ACTIVE SYSTEM COLLECTOR REQUIREMENTS-ABOVEGROUND TANK

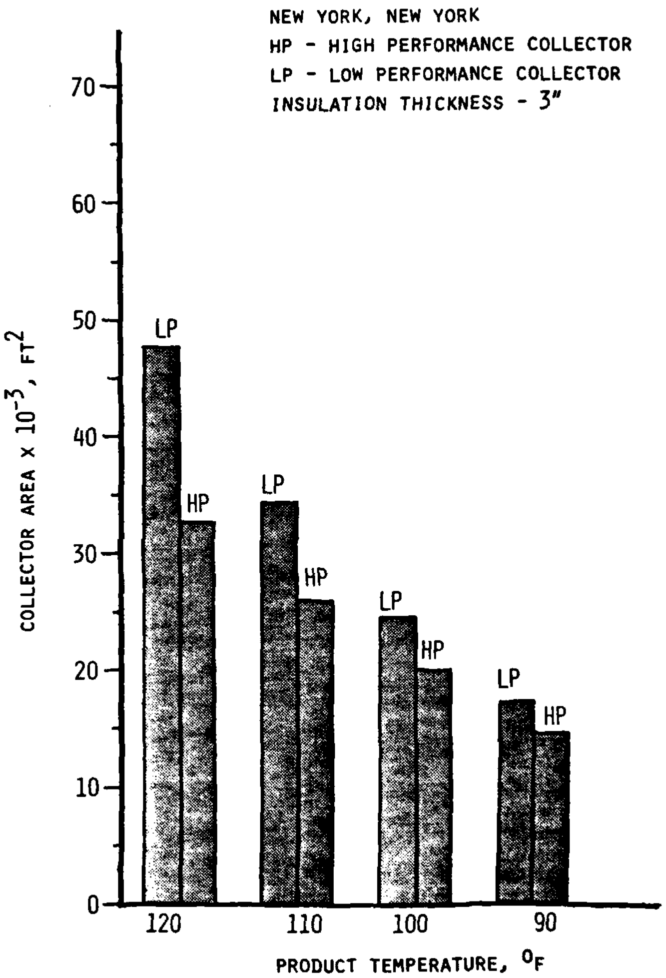

Figure 7-7b. ACTIVE SYSTEM COLLECTOR REQUIREMENTS-ABOVEGROUND TANK

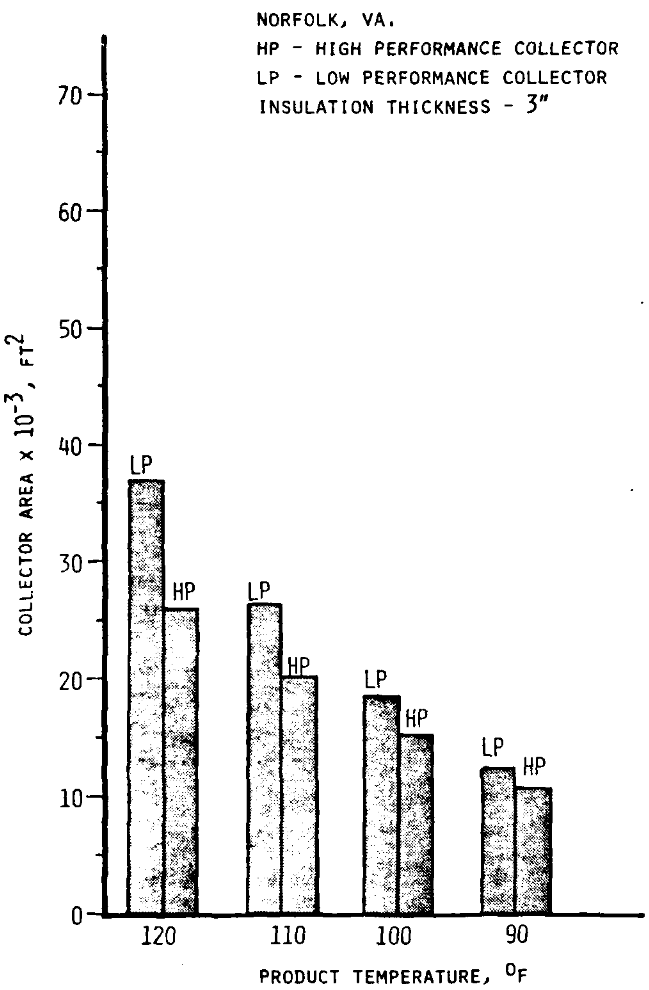

Figure 7-7c. ACTIVE SYSTEM COLLECTOR REQUIREMENTS-ABOVEGROUND TANK

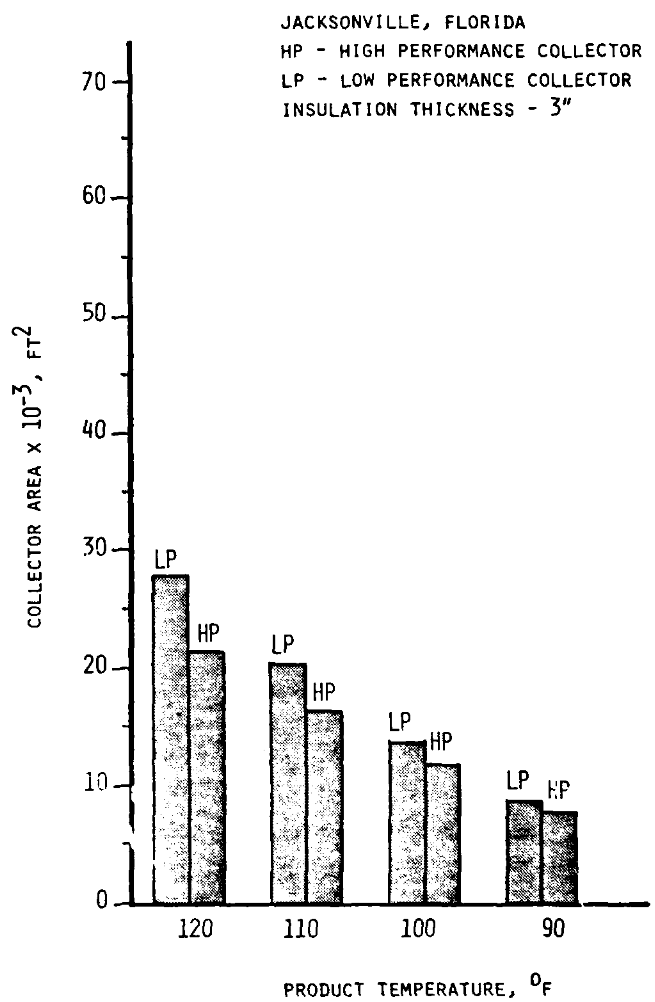

Figure 7-7d. ACTIVE SYSTEM COLLECTOR REQUIREMENTS-ABOVEGROUND TANK

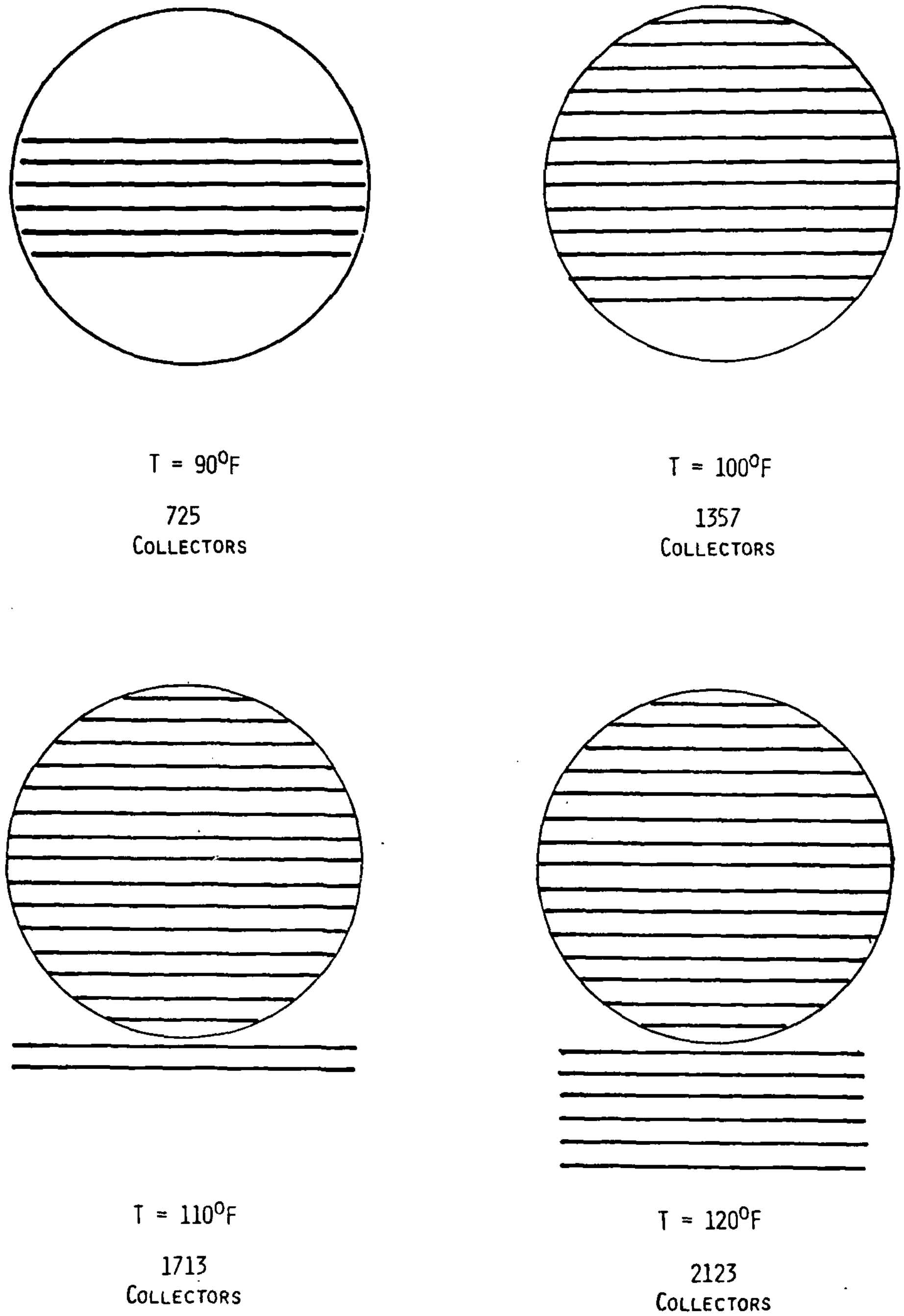

Figure 7-8a. ACTIVE COLLECTOR ARRAY LAYOUT
PORTLAND, MAINE; PLAN VIEW

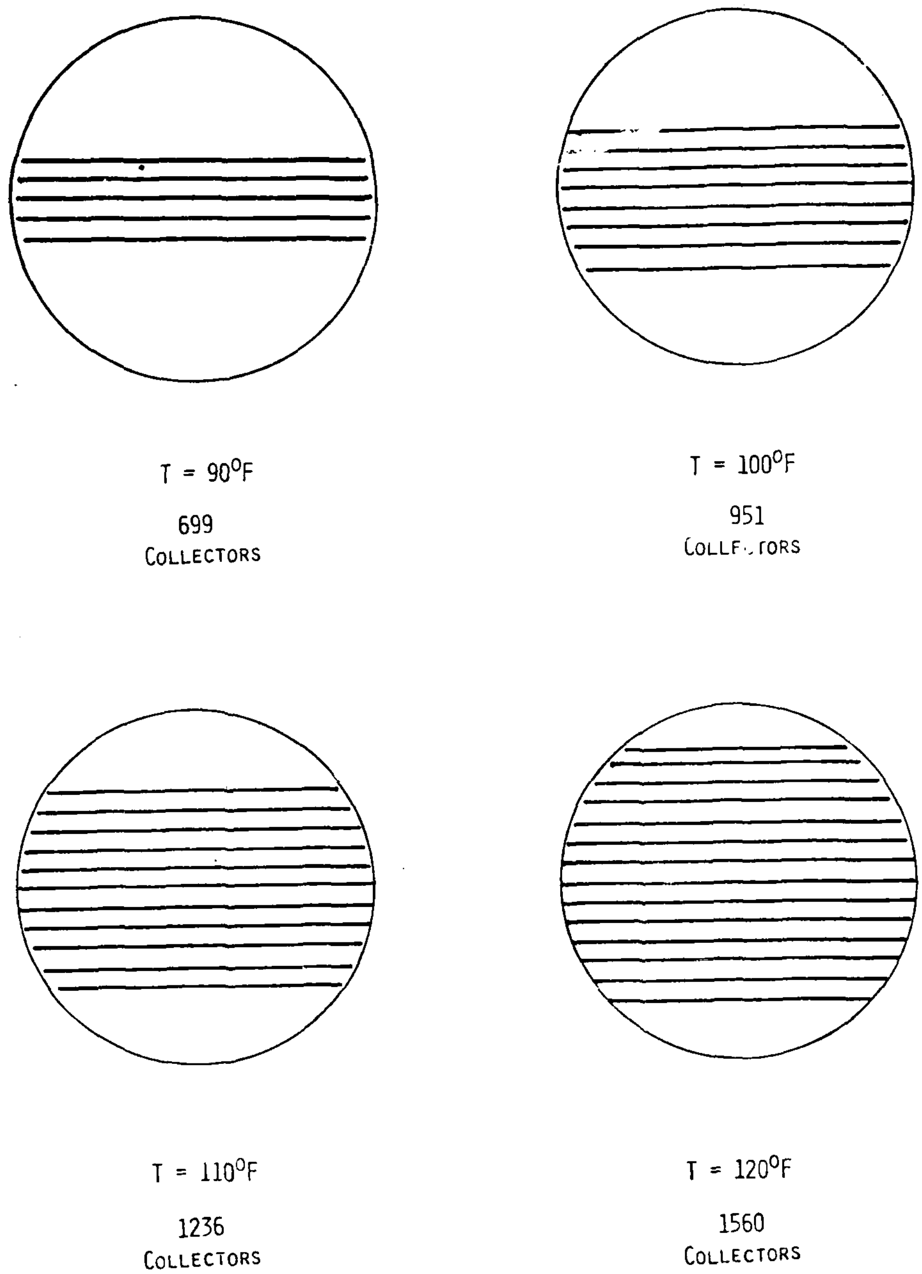

Figure 7-8b. ACTIVE COLLECTOR ARRAY LAYOUT
NEW YORK, NEW YORK; PLAN VIEW

AD-A144 651 EAST COAST REGIONAL PETROLEUM RESERVE (RPR) VOLUME 3 POTENTIAL STORAGE SI..(U) ARMY ENGINEER DIV HUNTSVILLE AL R E SHANNON ET AL. 30 SEP 80 HNDTR-80-45-SP-VOL-3

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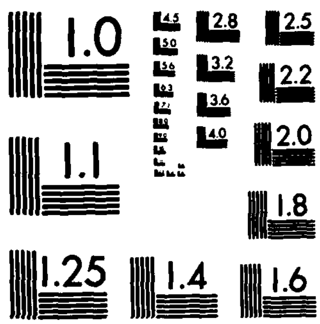


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

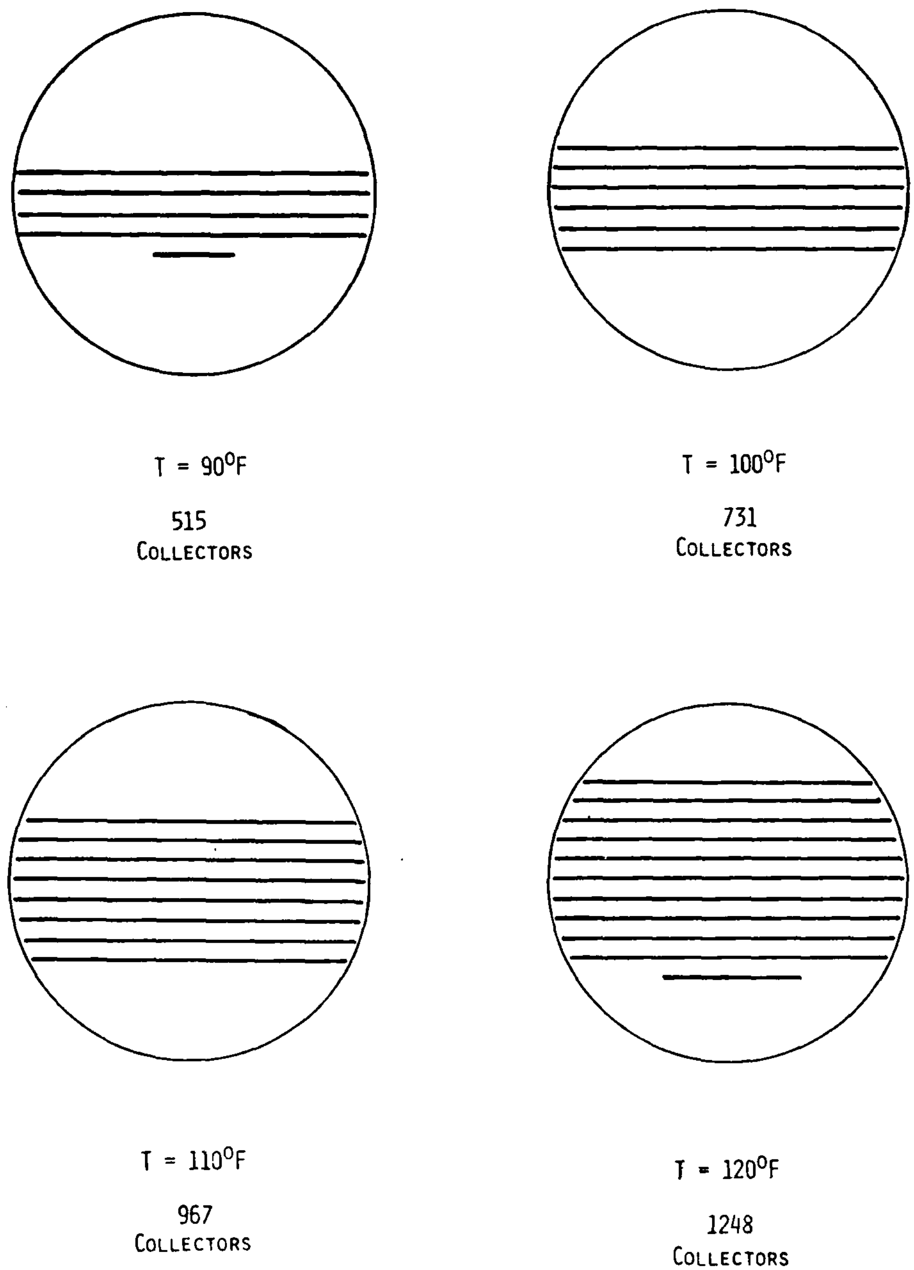


Figure 7-8c. ACTIVE COLLECTOR ARRAY LAYOUT
NORFOLK, VIRGINIA; PLAN VIEW

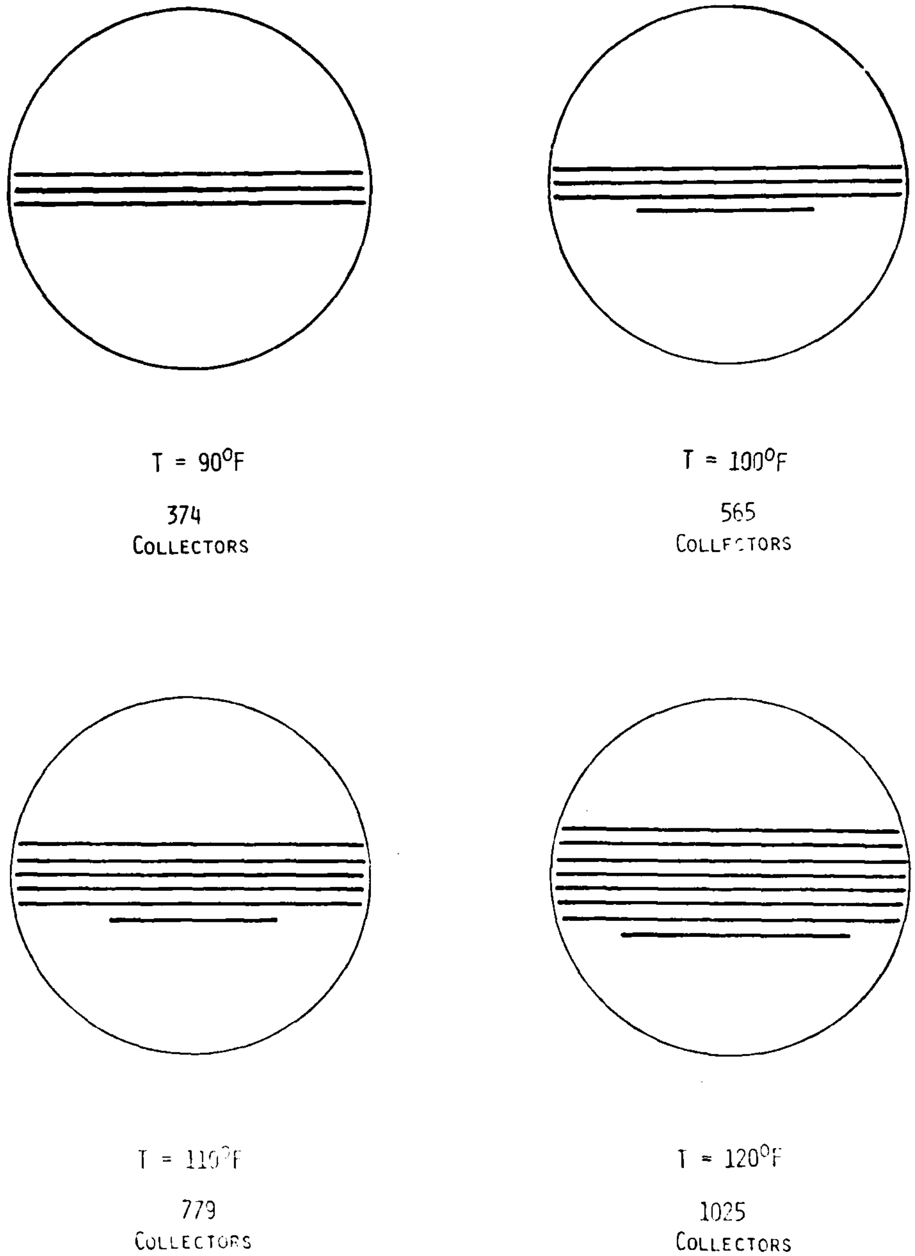


Figure 7-8d. ACTIVE COLLECTOR ARRAY LAYOUT
JACKSONVILLE, FLORIDA; PLAN VIEW

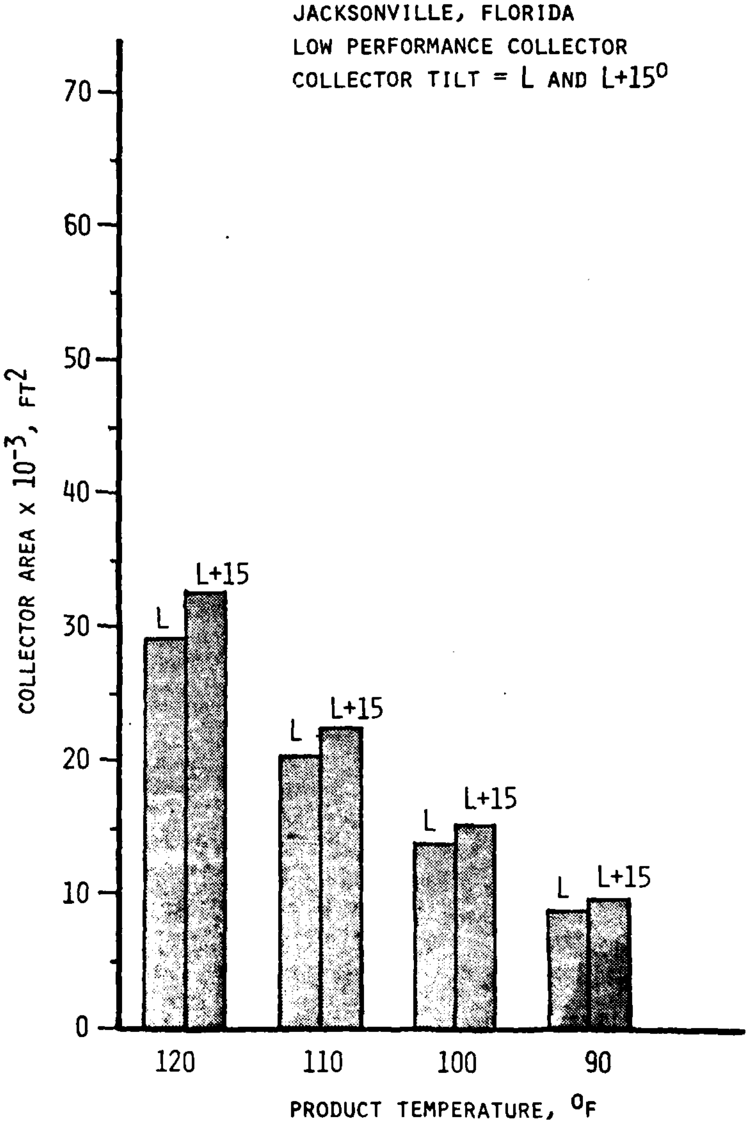


Figure 7-9. ACTIVE SYSTEM COLLECTOR REQUIREMENTS ABOVEGROUND TANK

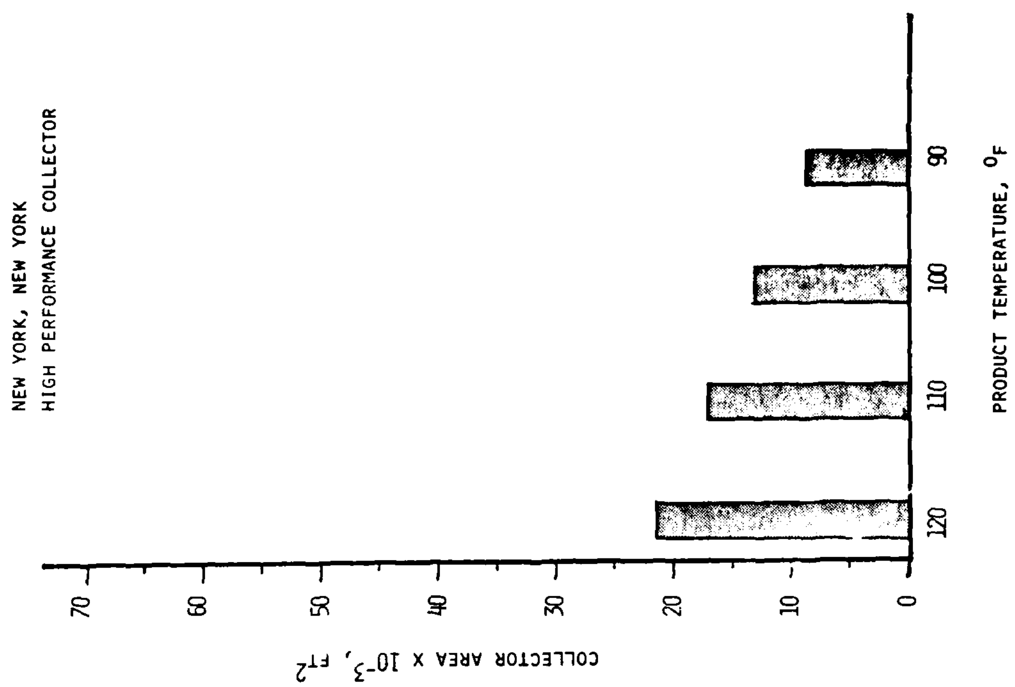


Figure 7-10b. ACTIVE SYSTEM COLLECTOR REQUIREMENTS-UNDERGROUND TANK

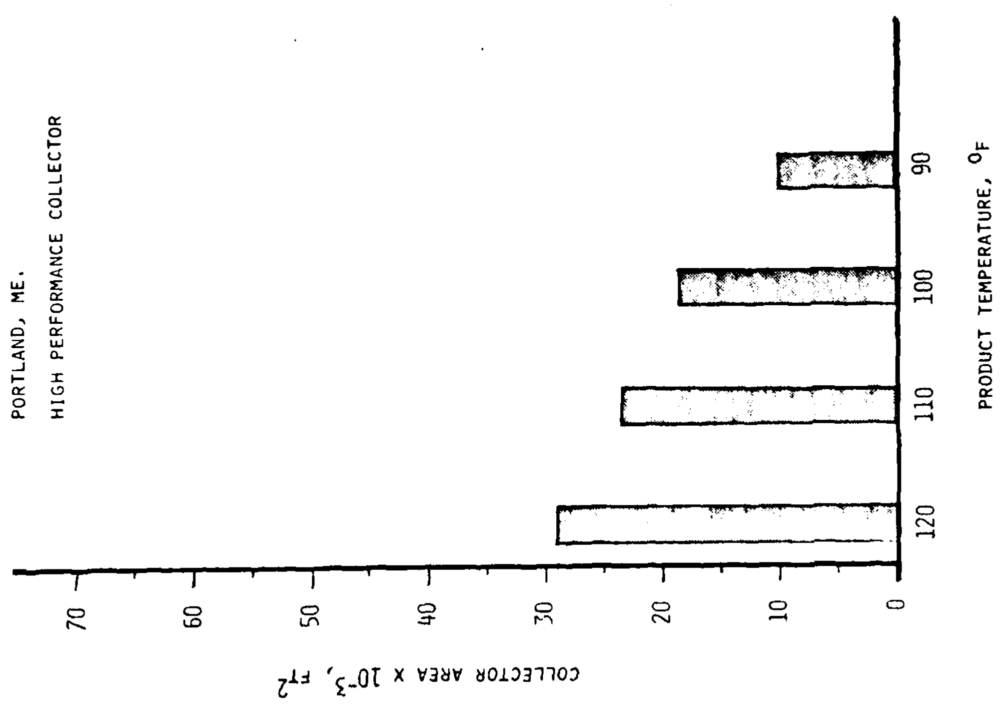


Figure 7-10a. ACTIVE SYSTEM COLLECTOR REQUIREMENTS-UNDERGROUND TANK

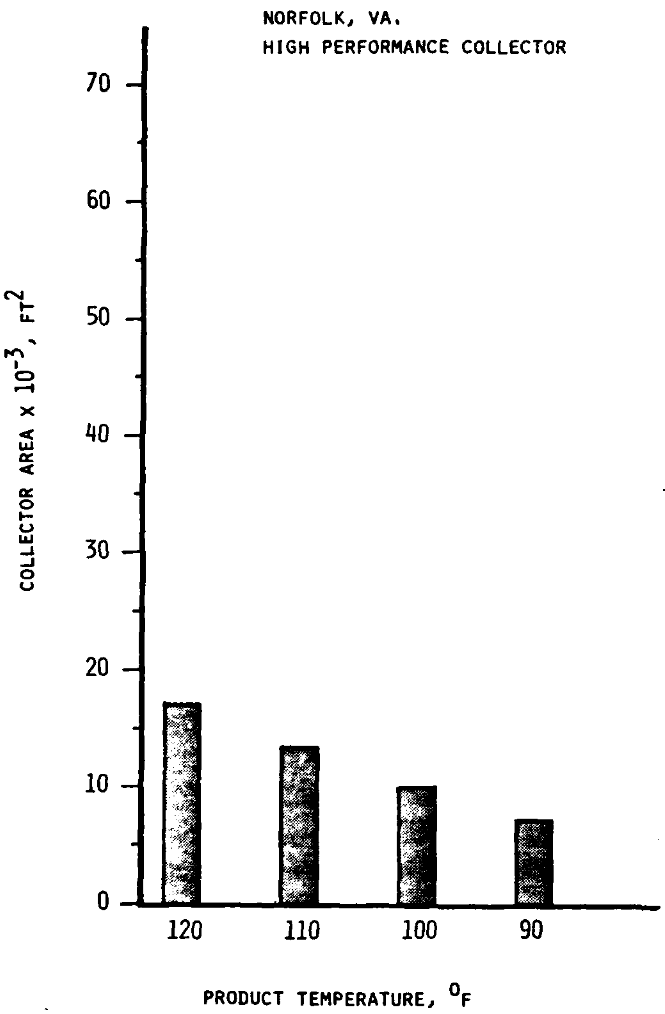


Figure 7-10c. ACTIVE SYSTEM COLLECTOR REQUIREMENTS-UNDERGROUND TANK

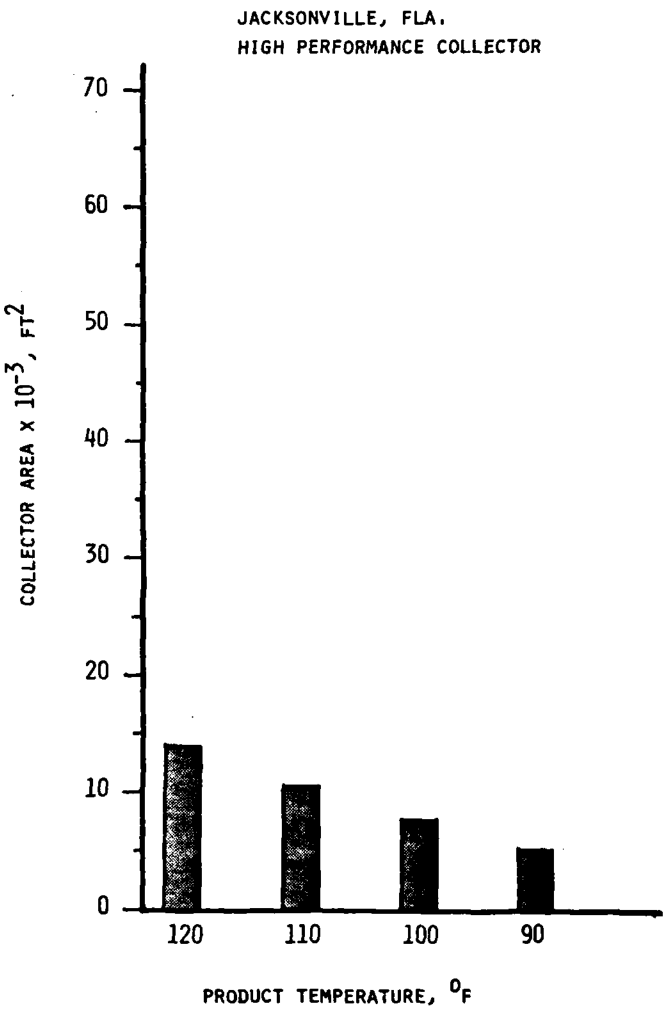


Figure 7-10d. ACTIVE SYSTEM COLLECTOR REQUIREMENTS-UNDERGROUND TANK

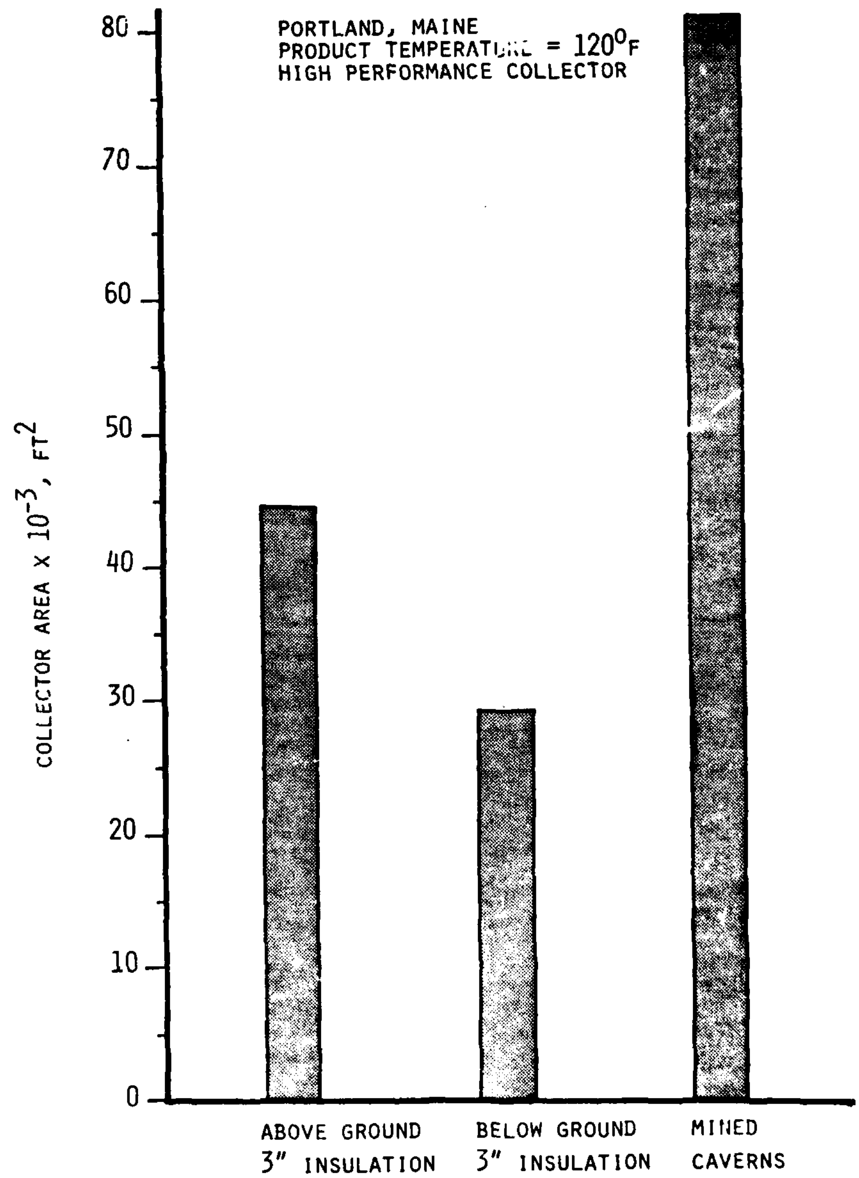


Figure 7-11. ACTIVE SYSTEM COLLECTOR REQUIREMENTS

To simplify calculations, a value of U_T at T - 110°F was chosen for all values of bulk temperature.

Now the transmittance-absorptive product ($\tau\alpha$) for a single-glazing is given by

$$(\tau\alpha)_n = \frac{\tau\alpha}{1-(1-\alpha)\rho_d} \tag{7-14}$$

$$= \frac{(0.9)\ (0.95)}{1-(1-0.95)\ (0.16)}$$

$$= 0.86$$

Transient Analysis Results: The steady-state analyses presented above considered only the long-term average temperature of the product. Because of the annual swings in ambient temperature, there is a possibility that the temperature of the product might reach unacceptable low temperatures in the winter, or unacceptable high temperature in the summer. Figure 7-12 presents a printout of the transient analysis computer program described in paragraph 7.2a. In this example (Portland) the temperature deviated roughly ± 5°F about the average temperature 110°F. Figure 7-12 illustrates the product temperature extremes for all sites investigated.

c. Passive System Collector Requirements

Two types of passive solar systems were considered in the detailed evaluations, an indirect gain collector and a direct gain collector. The indirect gain collector is composed of a double layer, vertical glazing attached outside the south tank wall with a small air space between the tank and the glazing. Sunlight passes through the glazing thereby heating the tank wall, which is painted a dark color. The product is heated on the interior surface of the wall by natural convection. Stirrers would be used to mix the product thus distributing the heat collected from the south wall to the north wall and throughout the tank.

The direct gain collector involves replacing a portion of the steel roof of the tank with a double-glazed window. Sunlight passes through the glazing in the roof and strikes the dark product in the tank where it is absorbed and warms the product directly. Stirrers are also used here to mix the product and distribute the heat from the product in the top of the tank to the bottom of the tank. These two concepts were illustrated in Figure 5-10.

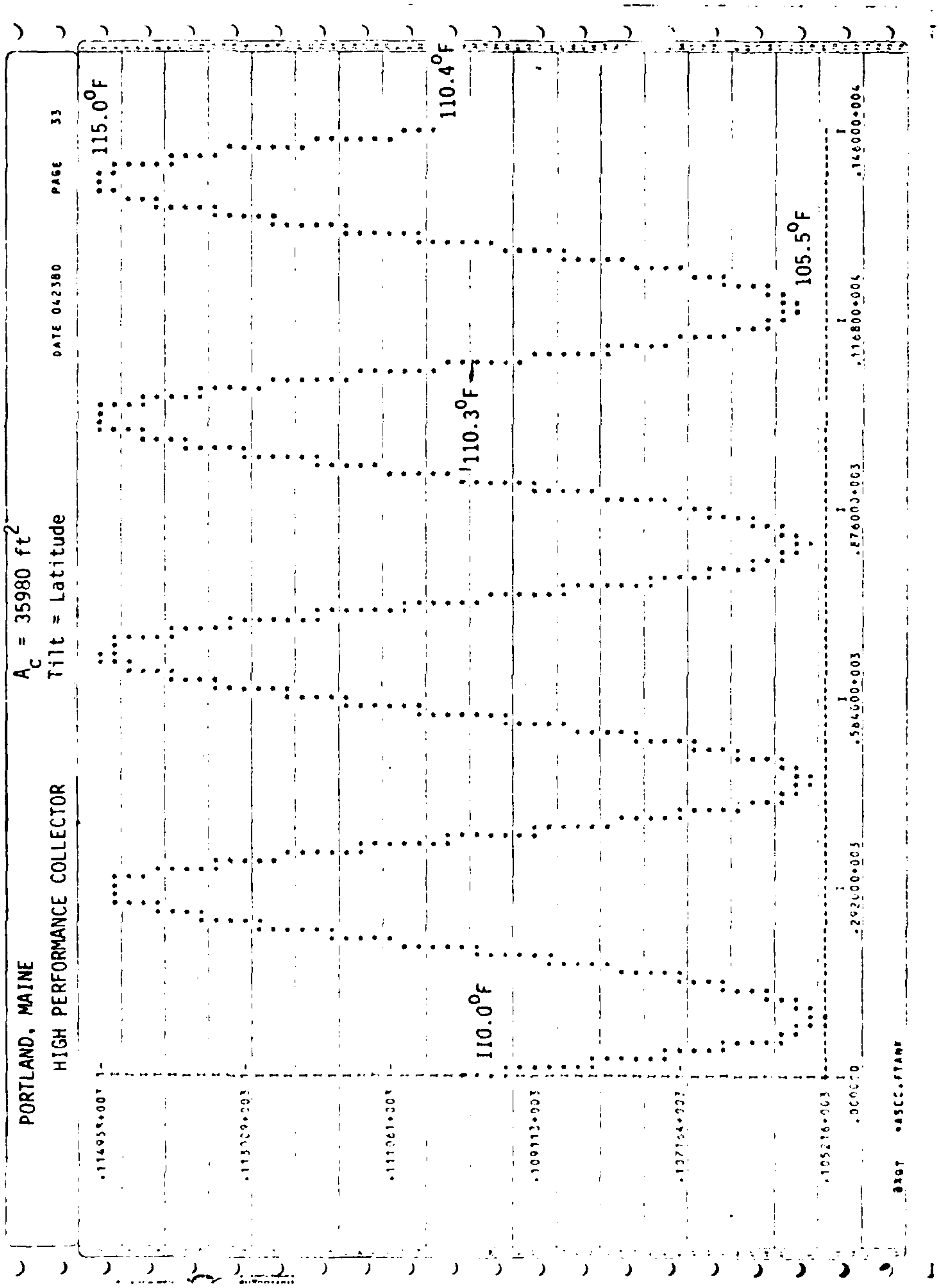


Figure 7-12. TEMPORAL VARIATION OF PRODUCT BULK TEMPERATURE

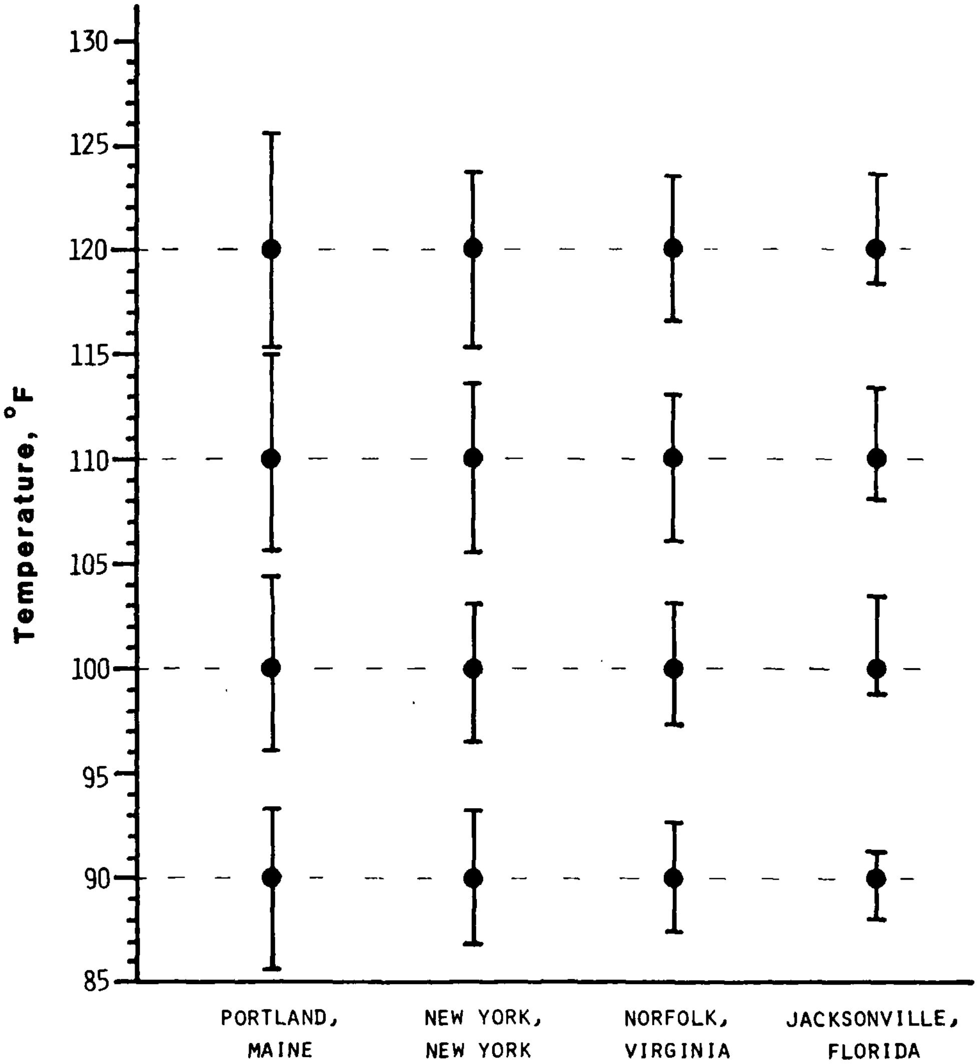


Figure 7-13. PRODUCT TEMPERATURE SWING

- HIGH PERFORMANCE ACTIVE SYSTEM -

Indirect Gain Collector Description: Passive heating systems constructed into the side of the storage tank offer the potential of low cost combined with high performance. Figure 7-14 is a cross-section of the collector surface illustrating the temperature profile through the glazing and tank wall.

Now

$$q_{in} = I\ (\tau\alpha) - q_{LOSS} \tag{7-12}$$

$$= I\ (\tau\alpha) - U_T(T_a - T_p) \tag{7-13}$$

The top surface heat loss coefficient, U_T, can be determined from Duffie and Beckman[13] and are shown in Table 7-6.

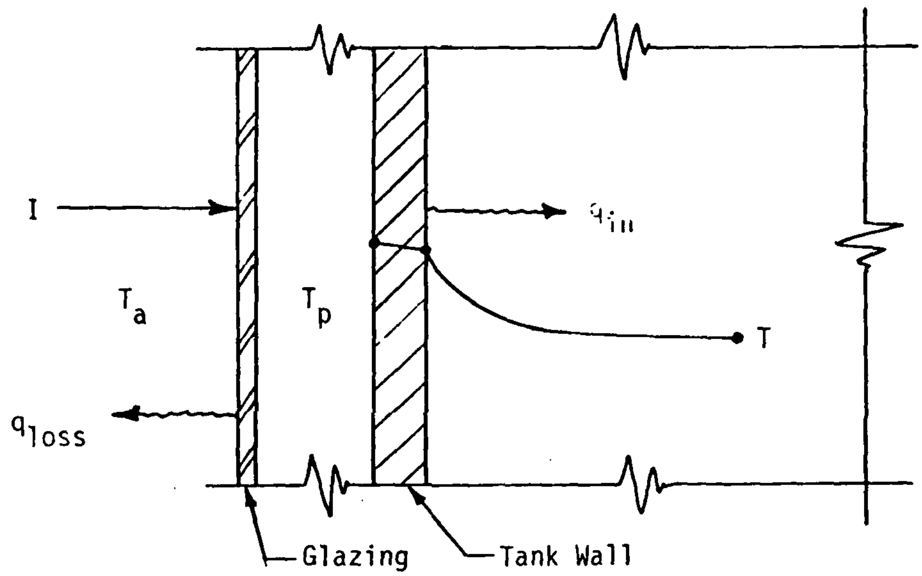


Figure 7-14. CROSS-SECTION OF INDIRECT GAIN COLLECTOR

Table 7-6. TOP HEAT LOSS COEFFICIENT
(V - 15 ft/sec)

T(°F)	1 cover	2 covers
120	1.21	-
110	1.16	0.57
100	1.11	-

[13]Duffie, John A. and William A. Beckman, "Solar Energy Thermal Processes," John Wiley & Inc.

And for a double-glazing

$$(\tau\alpha)_n = \frac{\tau\alpha}{1-(1-\alpha)\rho_d} \qquad (7\text{-}15)$$

$$= \frac{(0.83)(0.95)}{1-(1-0.95)\ (0.24)}$$

$$= 0.80$$

To account for reflections off the glazing at angles other than 90^o, an incident angle modifier $\frac{\tau\alpha}{(\tau\alpha)_n}$ is multiplied by the normal incident transmittance absorbance product.

$$\tau\alpha = (\tau\alpha)_n \ X \frac{(\tau\alpha)}{(\tau\alpha)_n}$$

A typical incident angle modifier is equal to 0.91. Therefore,

$$\tau\alpha = (0.80)\ X\ (0.9\text{.},\ = \underline{\underline{0.728}}$$

Indirect Gain Collector Evaluation: The heat balance on a secti of the vertical wall indirect gain collector gives (see Figure 7-15

$$I - I_{Reflected} = Q_{IN} \qquad (7\text{-}16)$$

$$= Q_{NET} + Q_{LOSS}$$

$$Q_{IN} - Q_{LOSS} = Q_{NET}$$

rewriting for heat loss on an annual basis.

$$Q_{IN} = \tau\alpha\ I_{ANNUAL} = 0.728\ I_{ANNUAL} \qquad (7\text{-}17)$$

$$Q_{LOSS} = U_{LOSS}\ (T - T_a)\ X\ 24\ \text{hr/day}\ X\ 365\ \text{days/yr} \qquad (7\text{-}18)$$

$$= 8760\ U_{LOSS}\ (T - T_a)$$

$U_{LOSS} = 1.16$ Btu/hr ft^2 ^oF single-glazed

$= 0.57$ Btu/hr ft^2 ^oF double-glazed

Q_{NET} is the annual change in energy added to the product. A net heat loss from the product ($Q_{NET}<0$) indicates that the passive system cannot supply the heat losses.

For a single-glazed indirect gain collector

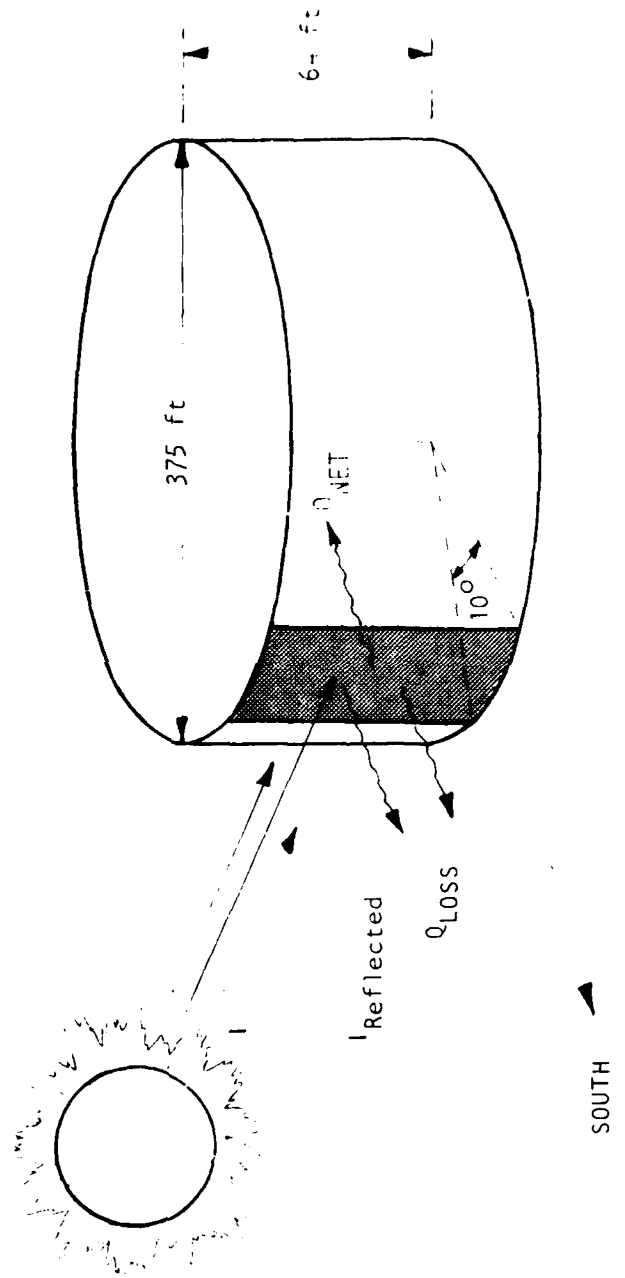


Figure 7-15. INDIRECT GAIN COLLECTOR

$$Q_{NET_S} = 0.728\ I_{ANNUAL} - 1.16 \times 8760\ (T - T_a) \tag{7-19}$$

$$= 0.728\ I_{ANNUAL} - 10162\ (T - T_a)$$

$$Q_{NET_D} = 0.728\ I_{ANNUAL} - 0.57 \times 8760\ (T - T_a) \tag{7-20}$$

$$= 0.728\ I_{ANNUAL} - 4993\ (T - T_a)$$

Since the indirect gain collector must be mounted on the curved wall on the tank, different parts of the collector face different azimuth angles to include the variation in solar radiation available at different azimuth angles. The annual solar radiation I_{ANNUAL} was calculated by the NASA method for azimuth angles from 0-90° in increments of 10° as descrived in paragraph 3.1.

Since the greatest solar radiation striking a vertical surface will most probably occur at the northern most site, the indirect gain collector was first evaluated at Portland, Maine. The net energy, Q_{NET}, is shown in Table 7-7 along with the solar radiation available and losses per square foot of indirect gain collector.

Since at all azimuth angles the net energy added to the product was negative based on this preliminary evaluation, the direct gain collector examined was a net energy loser and, thereby, not a feasible option. In Jacksonville, indirect gain collector was a net energy gainer but the quantity of energy collected was insufficient to balance tank envelope heat losses.

Table 7-8 presents the net energy gain for a tank located in Jacksonville. Since the net gain is positive there is a possibility that it can equal or exceed the total tank heat loss and, therefore, be a viable option. It was found that a collector with an included angle of 110° could indeed heat this tank. At a product temperature of 120°F, the indirect system could not provide enough net gain to offset the tank heat losses; therefore, without augmentation by reflectors or night curtains, it was concluded that the indirect passive system was not a viable option, except at low product temperatures and at Southeast site locations.

Direct Gain Collector: The heat balance on a unit of direct gain collector is given by

$$Q_{NET} = Q_{IN} - Q_{LOSS} \tag{7-21}$$

where the terms were previously defined for the indirect gain collector. If Q_{NET} is positive, then the direct gain collector is a net energy benefit, and the collector area required is that necessary to balance

Table 7-7. INDIRECT GAIN COLLECTOR ENERGY BALANCE
PORTLAND, MAINE, DOUBLE-GLAZED

$\bar{T} = 100^{o}F$, $\bar{T}_a = 45^{o}F$

Azimuth Angle	I_{ANNUAL} $10^6 Btu/yr/ft^2$	Q_{IN} $10^6 Btu/yr/ft^2$	Q_{LOSS} $10^6 Btu/yr/ft^2$	Q_{NET} $10^6 Btu/yr/ft^2$
0	247,581	180,239	274,615	-94,376
10	246,247	179,268	274,615	-95,347
20	242,420	176,482	274,615	-98,133
30	236,444	172,213	274,615	-102,483
40	228,810	166,574	274,615	-108,041
50	218,925	159,377	274,615	-115,238
60	203,537	148,175	274,615	-126,440
70	189,273	137,791	274,615	-136,824
80	174,379	126,948	274,615	-147,667
90	159,521	116,131	274,615	-158,484

Table 7-8. INDIRECT GAIN COLLECTOR ENERGY BALANCE
JACKSONVILLE, FLORIDA - DOUBLE-GLAZED

$T = 100^{o}F$, $\bar{T}_a - 65^{o}F$

Azimuth Angle	I_{ANNUAL} 10^6 Btu/yr/ft^2	Q_{in} 10^6 Btu/yr ft^2	Q_{net} 10^6 Btu/yr/ft^2
0	265,056	192,961	18,206
10	265,391	193,205	18,450
20	265,669	193,407	18,652
30	263,505	191,832	17,077
40	260,665	189,764	15,009
50	255,424	185,069	11,194
60	247,348	180,069	5,314
70	236,639	172,273	
80	224,357	163,328	
90	209,750	152,698	

the load of the remaining tank consisting of heat losses from the tank walls, perimeter, and bottom, plus the heat losses from the portion of the roof not in the collector. Now for 3 inches of tank insulation.

$$Q_{LOSS_{SIDES\ +\ BOTTOM}} = 7751\ \text{Btu/hr}^{o}\text{F} \times 8760\ \text{hr/yr}\ (\bar{T} - \bar{T}_a)$$

$$= 67.9 \times 10^6\ (\bar{T} - \bar{T}_a) \quad \text{Btu/yr} \qquad (7\text{-}22)$$

The insulated roof that is not composed of the direct gain collector has a heat loss

$$Q_{LOSS_{ROOF}} = 0.04507\ \text{Btu/hrft}^{2o}\text{F} \times 8760\ \text{hr/yr}\ (110{,}447\ \text{ft}^2 - A_c) \times (\bar{T} - T_a)$$

$$= 395\ (110{,}447 - Ac)\ (\bar{T} - \bar{T}_a) \quad \text{Btu/yr}$$

The collector area required for solar to match the heat losses of the insulated tank is:

$$A_c = \frac{111.5 \times 10^6\ (T - T_a)}{Q_{NET} + 395\ (T - T_a)} \quad \text{ft}^2 \qquad (7\text{-}23)$$

The direct gain collector area required for various locations and product temperature is shown in Figure 7-16 expressed as a percent of the roof. The broken bars indicate where the collector area requirements exceed the total roof area. It is at these conditions that the concept is not feasible. Figure 7-17 illustrates the product's temperature extremes as computed by the unsteady-state model. In every case, except one the roof area predicted by the transient analysis agreed closely with that predicted by the steady-state use. The exception is Norfolk where the transient analysis indicated that passive was unfeasible at 120°F.

d. Heat Pump Requirements

The Jacksonville, Florida site was evaluated as a potential application of the heat pump concept. For this site, it was assumed that the oil storage tank was located close enough to utilize waste heat from the Jacksonville Electrical Authority Northside plant on the St. John's River. The temperature of the river water varies between 53°F and 85°F and experiences a 10° temperature lift in the plant's condenser. Since the water proceeds from there to the heat pump where it is chilled 10° in the evaporator of the heat pump, the river water temperature is also the temperature of the water leaving the heat pump evaporator (assuming no heat losses or gains between the power plant and the heat pump). For a sinusoidal temperature variation of the river water, the heat pump COP can be easily calculated on a month-by-month basis using the performance data provided in paragraph 6.3. Figure 7-18 illustrates these performance parameters averaged over a season of operation.

The heat pump utilizes electrical energy which was generated by the conversion of an energy source such as coal, oil, or nuclear fission. To properly evaluate a heat pump, conversion losses must also be considered. For this example, it was assumed that the power plant conversion

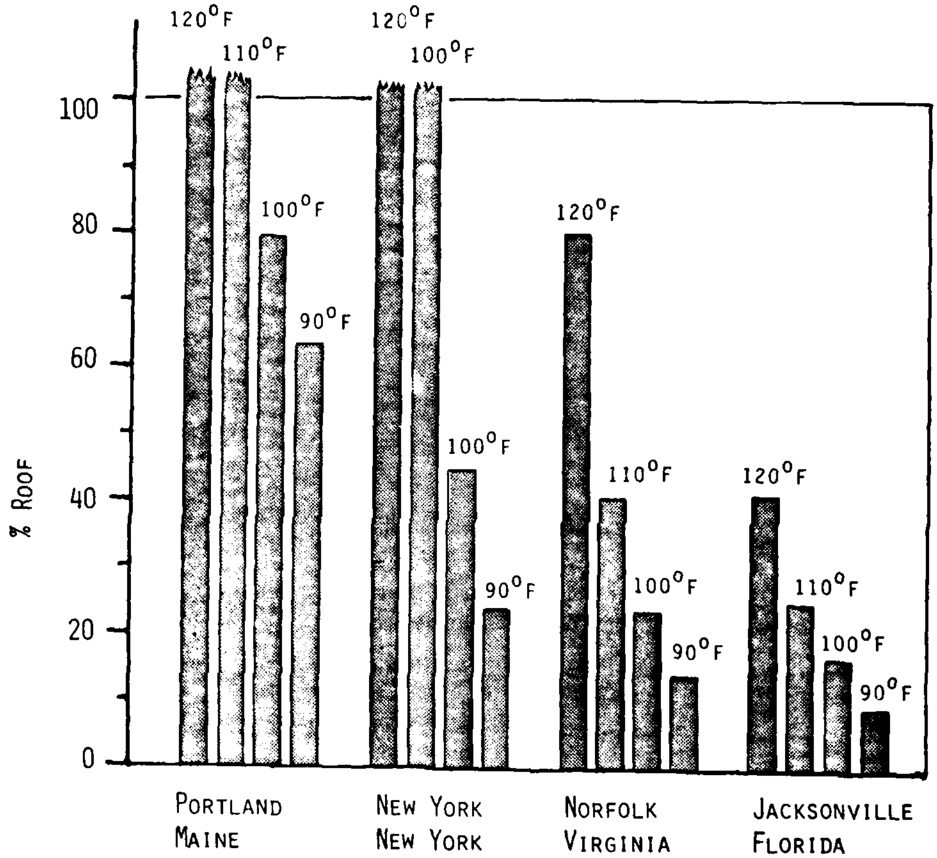


Figure 7-16. DIRECT GAIN ROOF COLLECTOR AREA

- DOUBLE-GLAZED -

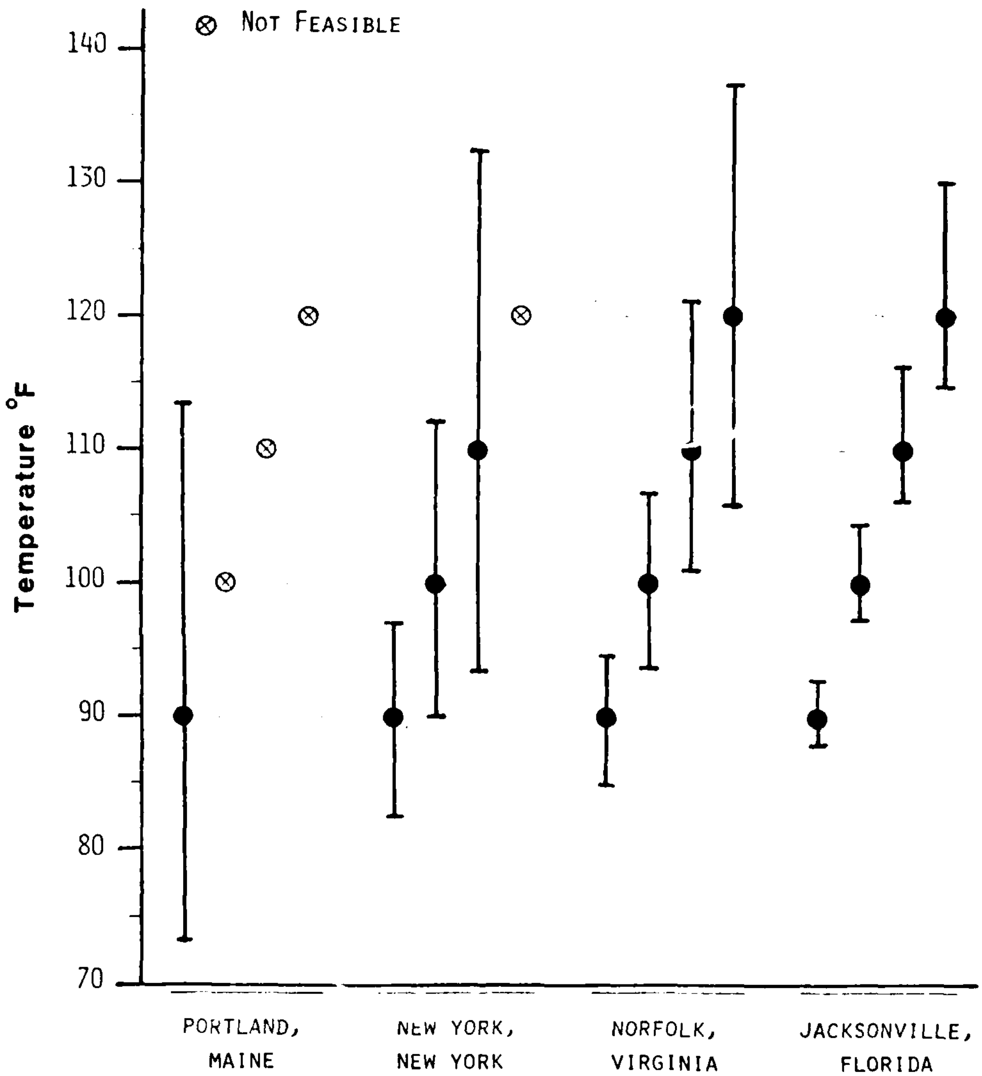


Figure 7-17. PRODUCT TEMPERATURE SWING

- DIRECT GAIN ROOF -

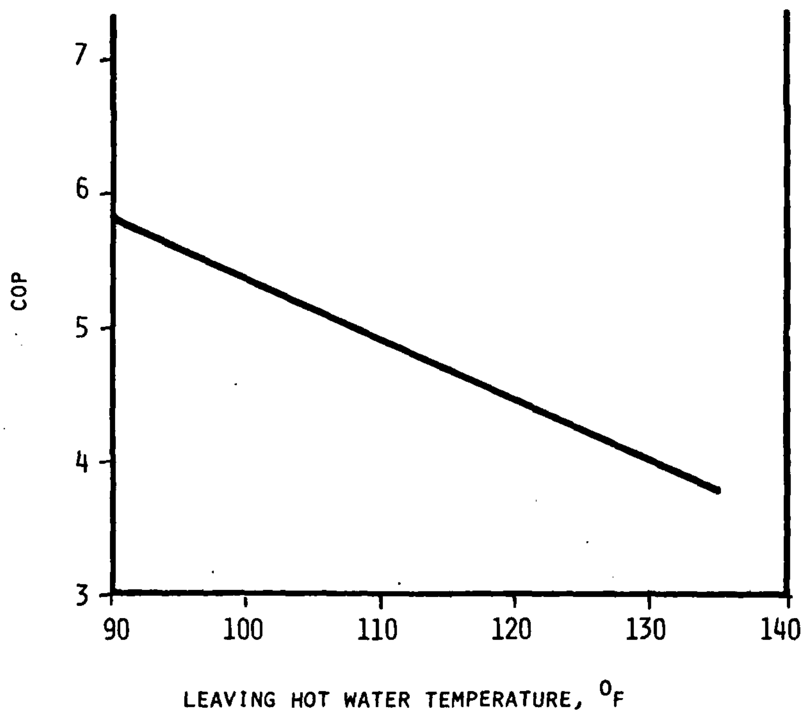


Figure 7-18. SEASONAL HEAT PUMP PERFORMANCE
JACKSONVILLE, FLORIDA

efficiency was 30 percent. It was also assumed that the power plant was operated as a boiler, e.g., only when it was necessary to extract the product in an embargo situation. In this operational mode the "load" is primarily the energy used to elevate the temperature of the product to the desired level, thus

$$Q = m\, c_p\, (T - \overline{T}_{am})$$

where

m = mass of product stored

c_p = specific heat of product

T = extraction temperature

$\overline{T}_{am}$ = equilibrium temperature of product (assume to be average ambient)

Thus, for each extraction the following amount of energy is required to elevate the product temperature

$$Q = 1.25\ (10^6\ \text{bbl} \times 42\ \text{gal/lb} \times 0.451\ \text{Btu/lb}^{\circ}\text{F} \times .99\ \text{Sp Gr} \times 8.34\ \text{lb/gal} \times (T - \overline{T}_{am})$$

$$= 195.5\ (10^6)\ \Delta T \qquad \text{Btu}$$

Figure 7-19 illustrates the source energy requirements for a single extraction for both the heat pump and the boiler, assuming the product is initially at the annual average temperature of 70°F for Jacksonville. Clearly, the heat pump has an advantage over the boiler in terms of source energy comsumption.

The rate at which the 1,250,000 barrels of product is to be extracted affects the size of the heat generating capacity, in this case the number of heat pumps. For this study, extraction durations of 45 days and 60 days were considered. Table 7-9 illustrates the number of machines required to achieve a given extraction temperature.

The heat pump can also be operated continuously to maintain the product at a desired temperature. Figure 7-20 illustrates the annual source energy requirements for both the heat pump and the boiler for this operational mode. Since the heat rate is low, only one heat pump is required to provide the desired capacity (except at a product temperature of 120°F where two are required).

7.3 SHADING ANALYSES

The length of the shadow cast by a vertical element of a tank is

$$l = \frac{h}{\tan \alpha}$$

where

h = height of tank
α = sun altitude angle

Since the sun is at a great distance from the earth, its rays are considered to be parallel and the shadow width is that of the tank.

Now

$$\sin \alpha = \sin L \sin \delta_s + \cos L \cos \delta_s \cos h_s$$

where

δ_s = declination angle

L = latitude

h_s = solar hour angle

$= 15^o$ (1200 - time of day)

The solar azimuth angle is

$$\sin \alpha_s = \frac{\cos \delta_s \sin h_s}{\cos \alpha}$$

Ground shadows cast by the tanks were defined for two location Portland and Jacksonville. These are presented in Figure 7-21.

Table 7-9. NUMBERS OF HEAT PUMP UNITS REQUIRED IN THE EXTRACTION MOL (1.25 MMB Tank)

WESTINGHOUSE TEMPLIFIER TPB - 060 A

	Product Temperature ^oF			
Extraction Duration	90	100	110	120
45 days	6	8	12	17
60 days	4	7	10	13

Note: For 10 MMB storage this number of units would be multiplied by 8.

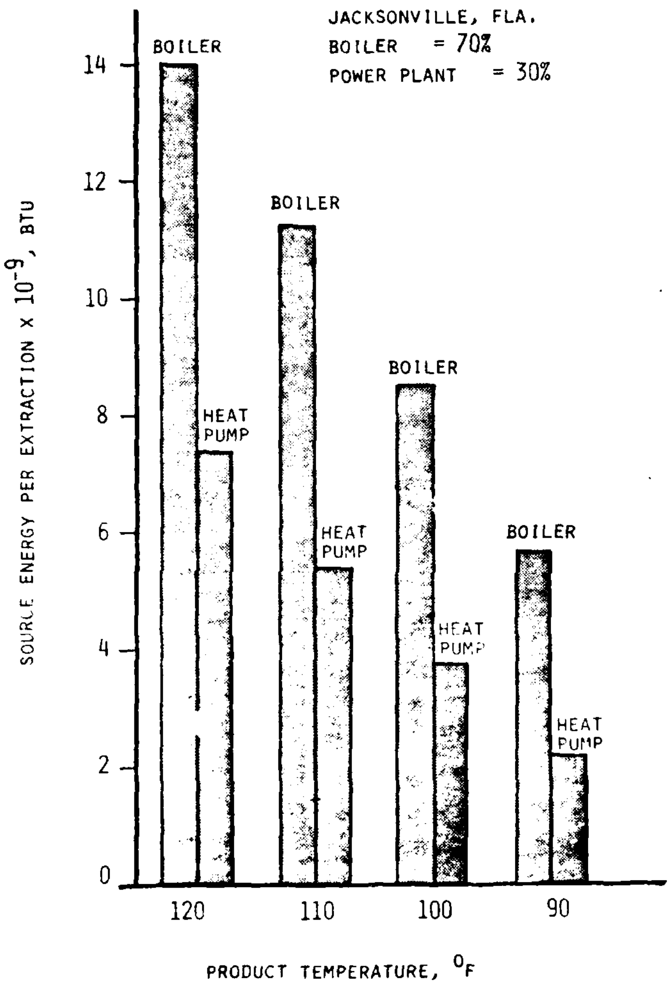


Figure 7-19. SOURCE ENERGY REQUIREMENTS - EXTRACTION MODE

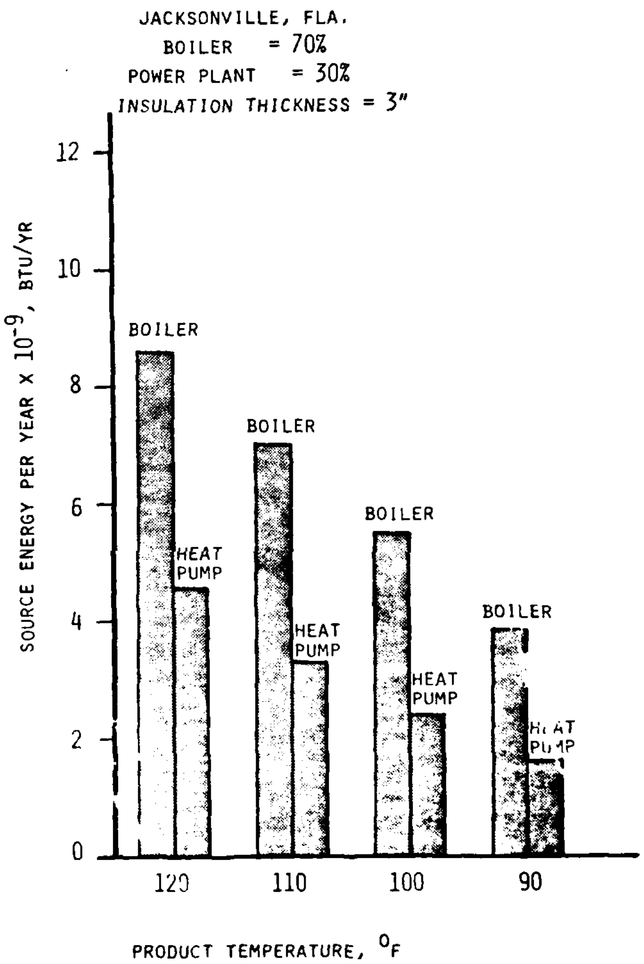
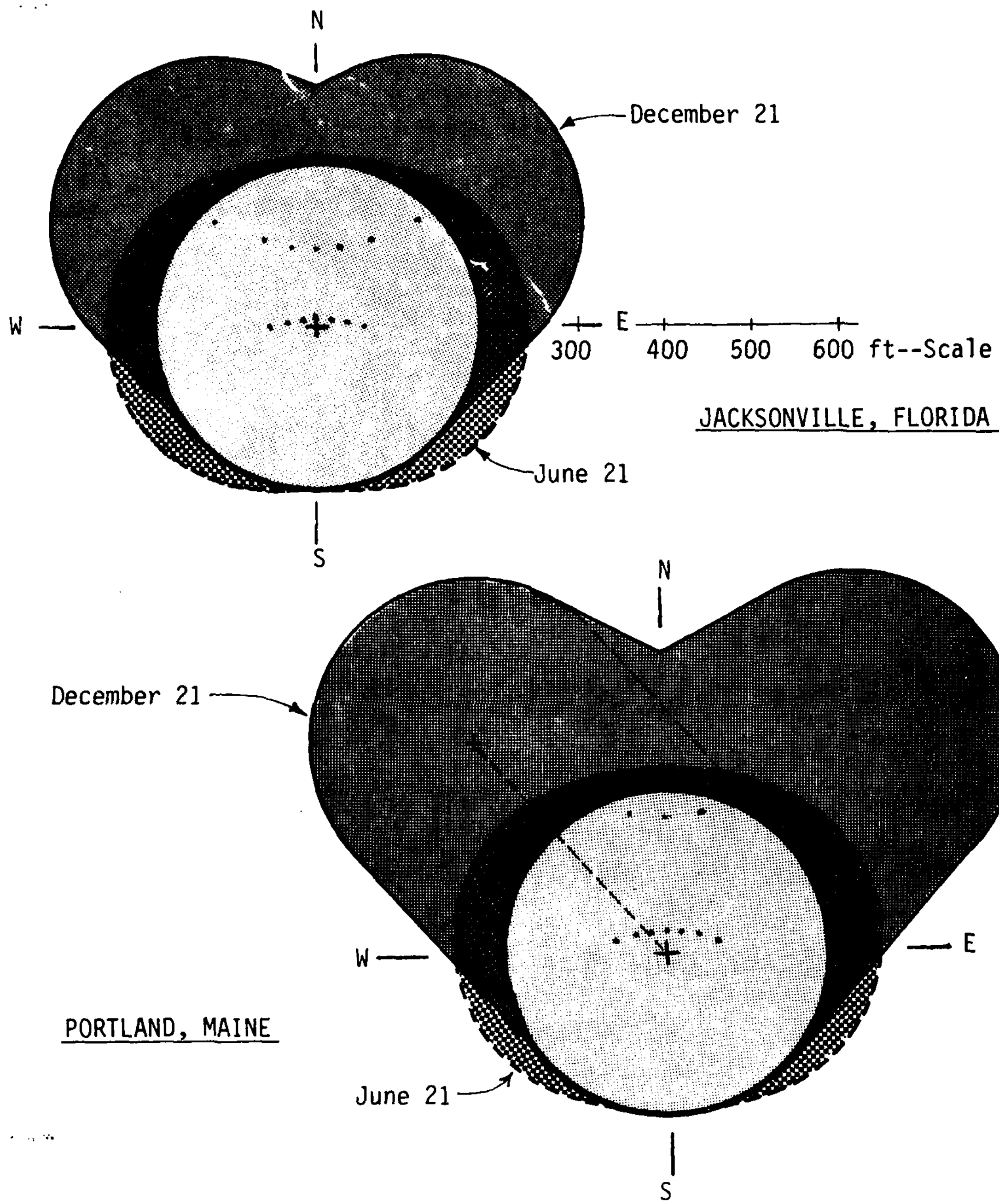


Figure 7-20. SOURCE ENERGY REQUIREMENTS - TEMPERATURE MAINTENANCE MODE



Note: Shading shows total area of shadow between 9am and 3pm.

Figure 7-21. GROUND SHADOW CAST BY TANK

CHAPTER 8
SOCIETAL/ENVIRONMENTAL/ATTITUDINAL CONSIDERATIONS

The choice of heating systems could very likely hinge on non-eco
Some of these are:

- environmental
- competition for limited fossil fuels
- *local economics*
- attitudinal

In the next few paragraphs these considerations will be discussed in terms of a solar heating system vs an oil-fired system.

8.1 ENVIRONMENTAL

The positive environmental benefits of solar have been well described through the literature. These are

- no atmospheric contamination from flue gases
- little or no potential for spill of stored fluids
- little requirement for depletable domestic resources
- potential for reduced site work.

8.2 COMPETITION

The entire idea of the Regional Petroleum Reserve Program is to provide for emergency supplies of residual oil in the event of an embargo. Heating the 1.25 million barrels of residual oil to a temperature satisfactory for withdrawal will require about 174,000 gallons of No. 2 oil,[14] energy that we can ill afford to consume in an emergency embargo situation. In effect, a solar heating system is equivalent to 174,000 gallons of No. 2 oil when it is needed the most.

---

[14] $$\text{Vol} = \frac{195.5\ (10^6)\ (120^\circ F - 45^\circ F)\,\text{Btu}}{140{,}000\ \frac{\text{Btu}}{\text{gal}} \times 0.6} = 174{,}554\ \text{gal}$$

See Paragraph 7.2d

8.3 LOCAL ECONOMICS

A solar system is potentially more labor intensive than an oil-fired heating system. The import on local trades and small businesses cannot be overlooked.

8.4 ATTITUDINAL

Public attitudes toward solar are almost without exception positive. This is in striking contrast to other energy technologies where public opposition to some new facilities must be a major consideration in planning.

APPENDIX A. HEAT TRANSFER FLUIDS

Reprinted from "Design and Installation Manual for Thermal Energy Storage", Argonne National Laboratory, ANL7916, Argonne, Illinois

APPENDIX A. HEAT TRANSFER FLUIDS

Heat transfer fluids are used in solar systems to transfer heat from the solar collector to the storage medium and from the storage medium to the building. They are sometimes called "collector coolants" because they cool the collector as they absorb its heat.

The fact that some heat transfer fluids and manufacturers are mentioned by name in this appendix as examples in no way constitutes endorsement or recommendation.

COMPARISON OF HEAT TRANSFER FLUIDS BY GENERAL CHARACTERISTICS

Air

Air is one of the most commonly used heat transfer fluids in solar systems. It is free and will operate at any temperature the solar system will reach. Moreover, a leak in an air-based system will cause no damage, although it will degrade system performance. Since air has a low volumetric heat capacity, its flow rate through the system must be high. The power used to transfer a given amount of energy is higher for air than for most liquids. The major disadvantage of air is that it requires large duct size, which makes retrofitting difficult and provides more area for thermal losses. Air handling systems are also generally noisier than liquid-based systems.

Water

Water is a readily available fluid with good heat transfer properties (i.e., high heat capacity, high thermal conductivity, and low viscosity). Its major drawbacks are its high freezing temperature, its expansion upon freezing, and its corrosive effect on common engineering materials (except copper). Also, its low boiling point can cause large pressures within the collector system under zero flow conditions. Water has no adverse biological or environmental effects.

Ethylene Glycol

Other than water, the most commonly used heat transfer liquids in flat plate collectors are water/ethylene glycol solutions. These common, colorless, odorless antifreeze solutions are also used in many other applications. Ethylene glycol is relatively inexpensive and available from many manufacturers. (See listings in the Thomas Register.) With corrosion inhibitors, aqueous ethylene glycol solutions can reduce the corrosive action and freezing temperature of water. These solutions are usually available in a wide range of concentrations and inhibitor levels. The thermal properties of the solutions (heat capacity, thermal conductivity, and viscosity) are poorer than those of water.

The boiling and flash points of aqueous ethylene glycol mixtures are low and can be easily reached under zero flow conditions. Glycols can oxidize to organic acids (such as glycolic acids) when exposed to air near boiling temperatures. The inhibitors used are designed to neutralize these extremely corrosive acids. Periodic maintenance and addition of inhibitors must be done if these fluids are used. Another major drawback to the use of ethylene glycol is its high toxicity.[1] Most plumbing codes require that ethylene glycol solutions be separated from potable water by double-walled heat exchangers.

Propylene Glycol

Propylene glycol has properties similar to those of ethylene glycol, except that propylene glycol has higher viscosity and is less toxic. With inhibitors, propylene glycol can be used with most common engineering materials. Periodic maintenance and inhibitor addition must be performed to limit corrosion. Propylene glycol will also form acids at high temperatures in oxygen-rich atmospheres. Because of its lower toxicity, propylene glycol has been widely used in the food industry. Most manufacturers who produce ethylene glycol also market propylene glycol. The higher viscosity of propylene glycol makes the heat transfer properties of aqueous proplyene glycol mixtures poorer than those of ethylene glycol.

Other Glycols

Other glycol solutions have been used as heat transfer fluids in industry applications. These include diethylene and triethylene glycol. With inhibitors, both of these fluids can be used with higher boiling points than ethylene glycol. The thermal properties of these aqueous solutions are similar to those of ethylene glycol at similar concentrations. The vapor pressure of each is slightly higher than that of ethylene glycol. The toxicity of these fluids is between that of ethylene and propylene glycol; their cost is slightly higher than that of ethylene and propylene glycol.

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[1] The U.S. Federal Food, Drug and Cosmetic Act of 1938, a big step in the formation of the U.S. Food and Drug Administration (FDA), was prompted mainly by a poisoning episode in 1937 involving at least 73 deaths and perhaps as many as 107 deaths caused by diethylene glycol contained in a drug known as "Elixir Sulfanilamide" (Campbell). Diethylene glycol is somewhat less toxic than ethylene glycol.

Other glycol heat transfer compounds include polyalkylene glycols such as Ucon[2] brand fluids and Jeffox[3] brand fluids. With inhibitors, the corrosive action of these compounds upon common engineering materials can be reduced. They are low in toxicity and are available in a wide range of viscosities. Fluids of this type that are applicable to heat transfer purposes cost more than the other glycol compounds.

Petroleum (Mineral) Oils

Petroleum oils are also used as heat transfer fluids in industry applications. They generally are fluids designed to operate at high temperatures, although some are able to offer lower temperature operation. As a group, they have poorer heat transfer properties than water, with lower heat capacity and thermal conductivity and higher viscosity. The flash point and boiling point lie below possible zero flow temperatures of a collector. Upon exposure to air at high temperatures, these fluids are subject to oxidation and cracking, forming tars and other by-products that will reduce collector performance and increase corrosion. The toxicity of these fluids is generally low and their prices are relatively low. Mobiltherm[4] Light brand fluid was chosen in this study as a good representative of this class of fluids for low temperature applications.

Silicone Fluids

Some flat plate collector installations have used silicone fluids as the heat transfer fluids. They are produced by Dow Corning and General Electric, among others. These fluids have low freezing and pour points, low vapor pressure, low general corrosion, good long term stability, and low toxicity. Their major drawbacks are high viscosity, causing poor heat transfer and requiring higher flow rates, and high cost. Also, leakage through fittings can create problems because silicone fluids have lower surface tension than aqueous solutions. Joints and fittings must be adequate to insure minimal leakage.

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[2] Ucon is a trademark of Union Carbide Corporation.
[3] Jeffox is a trademark of Jefferson Chemical Company, Inc.
[4] Mobiltherm is a trademark of Mobil Oil Corporation.

Other Fluids

Another possible fluid for use in flat plate collectors is Dowtherm[5] J brand fluid. It is an alkylated aromatic compound with low viscosity, low heat capacity, and low thermal conductivity it is relatively inexpensive but has low flash and fire points. Oxidation of Dowtherm J at high temperatures upon exposure to air can lead to formation of insoluble materials and increased fluid viscosity. When the fluid is overheated, the flash point can be lowered and vapor pressure increased. If it is contaminated by other fluids (such as water), corrosion can be enhanced (in the case of water, steel). The toxicity of Dowtherm J is high. As with aqueous ethylene glycol solutions, double walls would most likely have to separate the potable water from the Dowtherm J.

Some other possible heat transfer fluids include Therminol[6] 44 brand ester-based fluid, Therminol 55 brand alkylated benzene fluid, and Therminol 60 brand hydrogenated aromatic fluid. They have low heat capacities, low thermal conductivity, high viscosity, and low freezing temperatures. The flash points of these fluids are at the upper range of possible zero flow temperatures. The costs of Therminol 44 and 60 are relatively high, while Therminol 55 is much less costly.

Sun-Temp[7] brand fluid, a saturated hydrocarbon, is another possible heat transfer fluid available to flat plate collector users. It has low heat capacity, low thermal conductivity, high viscosity, a low freezing temperature, a high boiling temperature, low toxicity, low corrosivity with aluminum, and low vapor pressure. It is relatively inexpensive. Because of its high viscosity, larger flow rates are required to produce turbulent flow and to increase heat transfer.

Recently, inorganic aqueous salt solutions have been proposed as possible heat transfer fluids. According to Kauffman, 23-percent sodium acetate and 38-percent sodium nitrate aqueous solutions with suitable additives can be used as heat transfer fluids. These solutions have low toxicity. Their cost is comparable to that of ethylene glycol, and their heat transfer properties are similar to those of the glycols. Pumping costs for these fluids would be low. Like other aqueous solutions, they are subject to boiling at lower temperatures with large vapor pressures. These fluids are still being investigated for solar energy applications.

COMPARISON OF HEAT TRANSFER FLUIDS BY PHYSICAL PROPERTIES

In the preceding discussion of heat transfer fluids, general characteristics of each fluid studied were discussed. In the following sections, the following physical properties will be considered.

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[5] Dowtherm is a trademark of Dow Chemical Company.
[6] Therminol is a trademark of Monsanto Company.
[7] Sun-Temp is a trademark of Research Technology Corporation.

- Thermophysical properties
- Flow rate
- Cost
- Toxicity
- Flammability
- Corrosiveness
- Vapor pressure
- Freeze protection

The heat transfer fluids discussed earlier will be compared to offer a quantitative description of probable performance in double-loop heat exchanger collector systems. In some sections, representative fluids were chosen for the comparison. For ethylene glycol a 50-percent aqueous solution with inhibitors was used. Because most properties of the glycols are not drastically different from manufacturer to manufacturer, we did not always compare each available ethylene or propylene glycol product. A 50-percent solution for both ethylene and propylene glycols was used, since this allows adequate freeze protection for most cases. For some applications, lower concentrations might be plausible; in such cases, the results found here will be slightly conservative for heat transfer and flow rate properties. Also, since the properties of diethylene and triethylene glycol are close to those of ethylene glycol, we did not consider it necessary to compare these fluids in every section.

Thermophysical Properties

The thermophysical properties of the fluids were found from the manufacturers' specifications over the operating temperature range of flat plate collectors. For heat transfer, water is the best fluid. It has a high heat capacity, high thermal conductivity, and low viscosity. Water and the other heat transfer fluids are compared in Figures A-1 through A-4 for the following thermophysical properties.

- Viscosity
- Heat capacity
- Thermal conductivity
- Density

Generally, aqueous solutions (such as ethylene and propylene glycol) have better thermophysical properties than do the rest of the heat transfer fluids except Dowtherm J. Dowtherm J has a lower viscosity than glycol solutions but also has lower heat capacity and thermal conductivity. Other simple comparisons of the heat transfer fluids can be made from Figures A-1 through A-4.

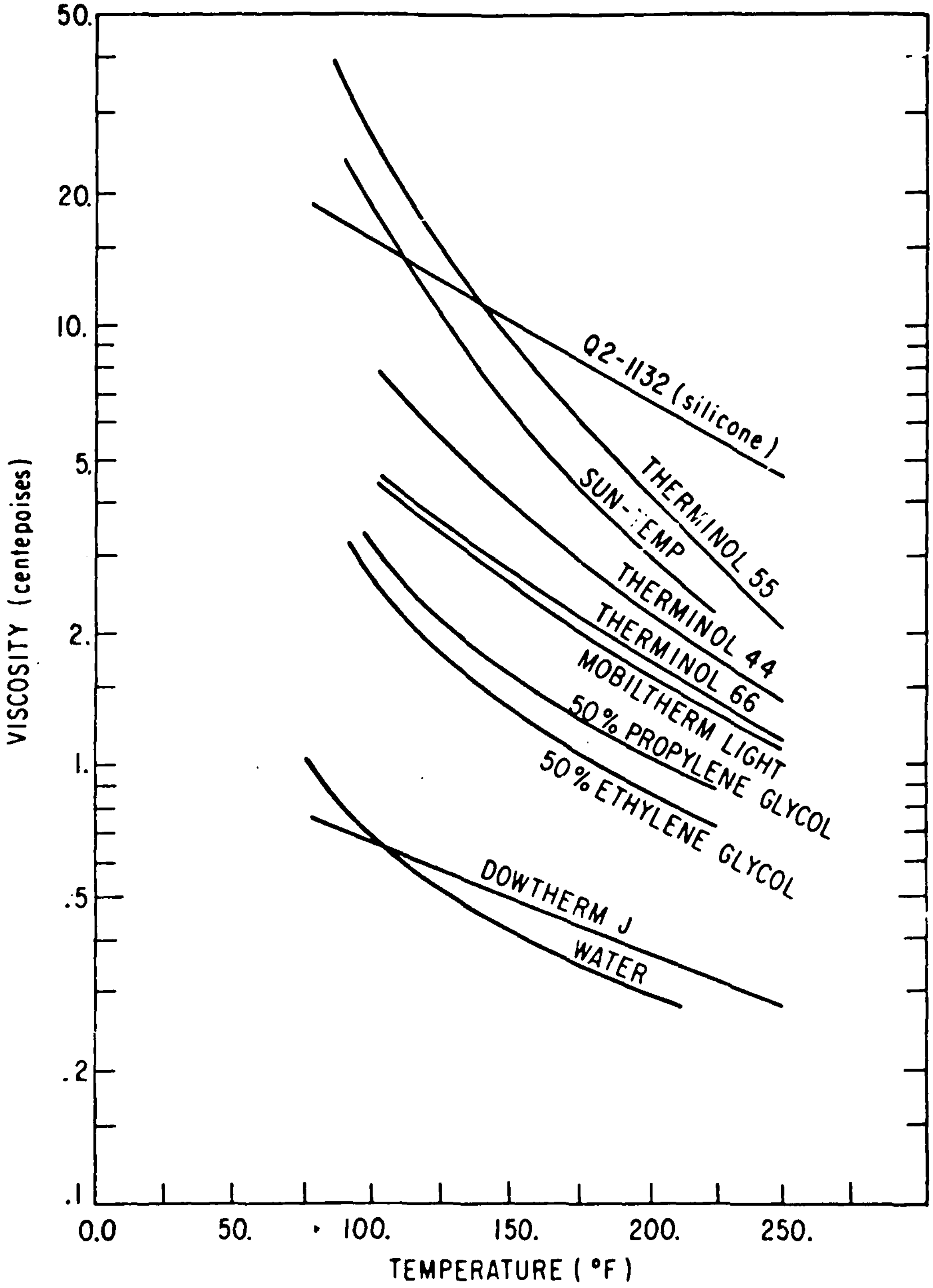

Figure A-1. Viscosity of Heat Transfer Fluids Versus Temperature (Multiply centipoises by 2.419×10^{-4} to get lb/ft·hr.)

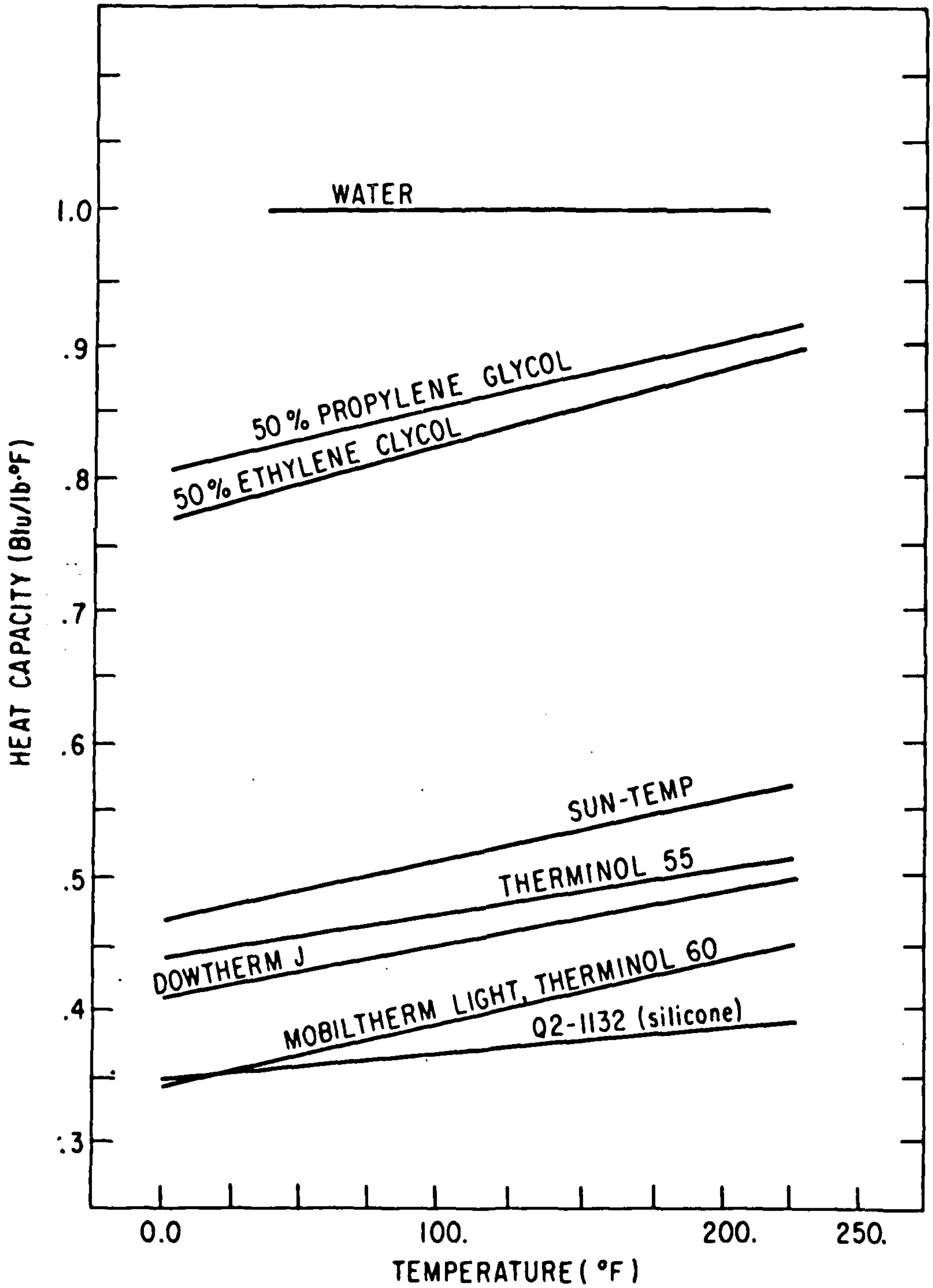

Figure A-2. Heat Capacity of Heat Transfer Fluids Versus Temperature

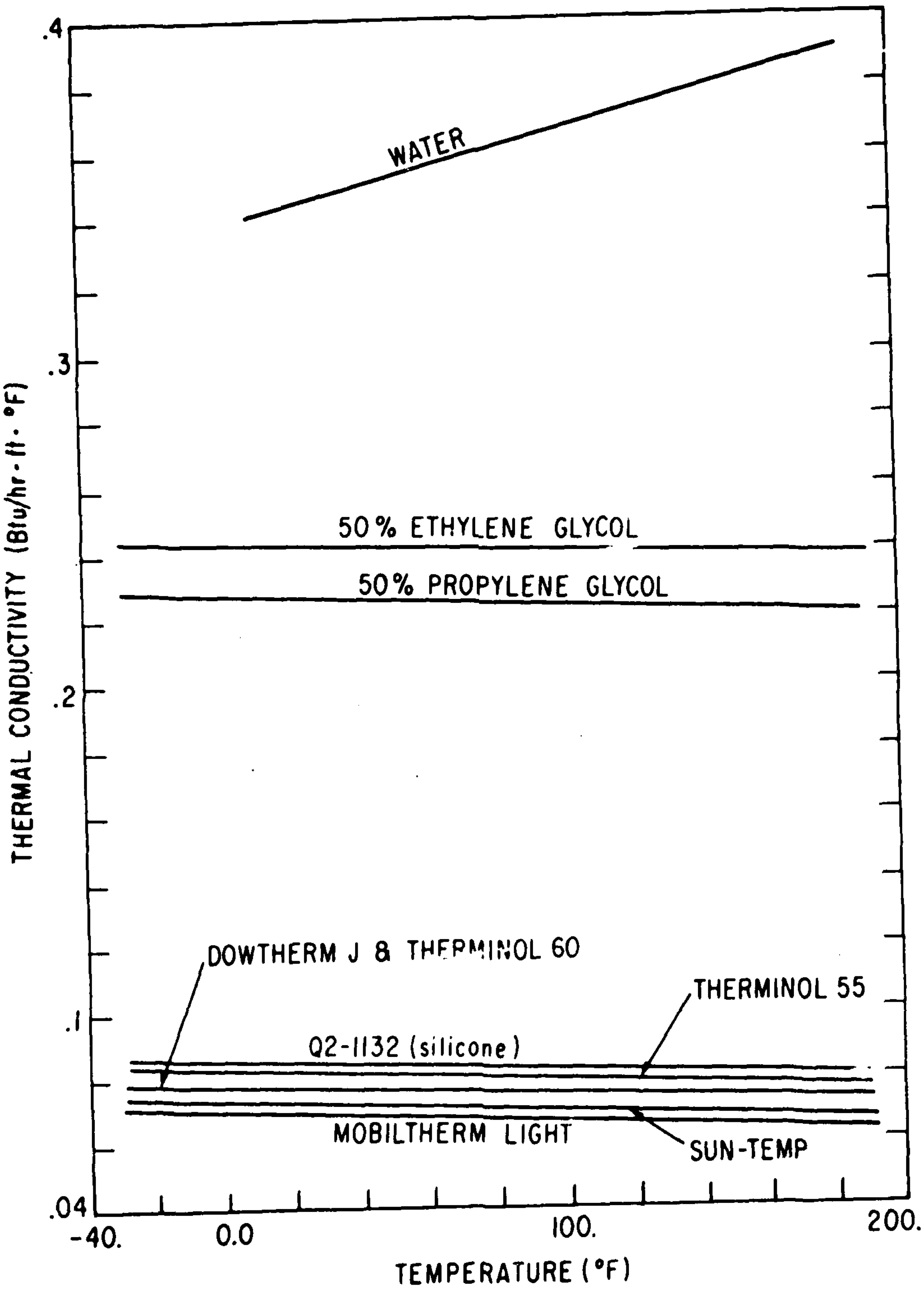

Figure A-3. Thermal Conductivity of Heat Transfer Fluids Versus Temperature

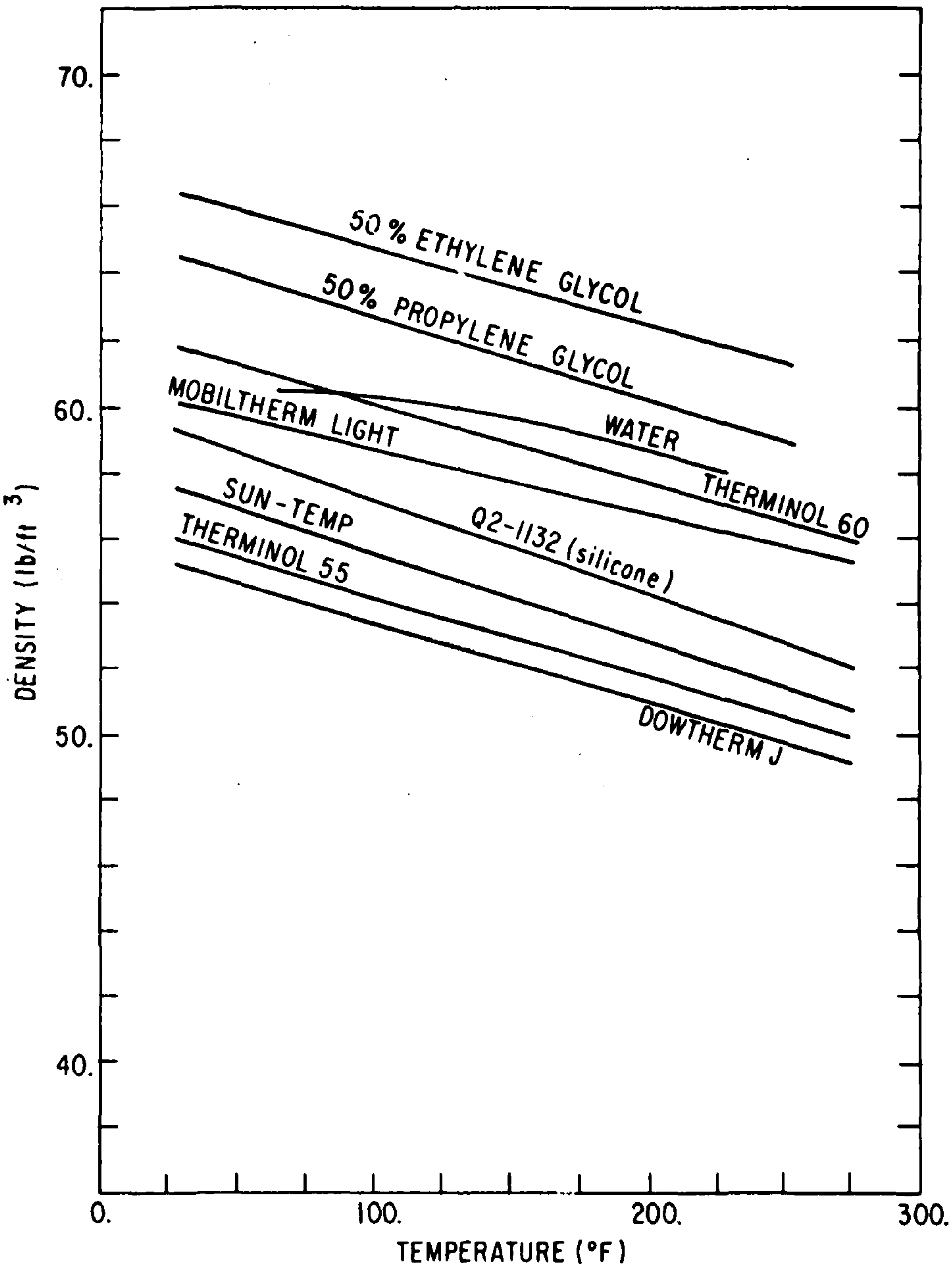

Figure A-4. Density of Heat Transfer Fluids Versus Temperature

Flow Rate

One of the important parameters to be considered in selecting a heat transfer fluid is the operating pressure drop caused by friction within the fluid channel. The pressure drop of the fluids was investigated for various flow rates and fluid channel sizes. McAdams found the pressure drop per tube length within tubes to be:

$$\frac{\Delta P}{L} = \frac{f\, G''^2}{2\, D_i g \rho\, 144} \quad \text{(psi/ft)} \qquad \text{A-1}$$

This neglects entrance and exit effects. Equation A-1 is applicable for collector, heat exchanger, and traced tank tubes where:

f = friction factor

= $16/Re$, for $Re < 2500$ (laminar flow)

= $0.0014 + 0.125/Re^{0.32}$, for $Re > 2500$ (turbulent flow in smooth-walled tubes)

Re = Reynolds number

= $G'' D_i/\mu$

μ = fluid viscosity (lb/ft·hr)

G'' = mass flow rate through tube (lb/hr·ft^2)

D_i = tube inside diameter (ft)

g = acceleration of gravity

= 4.18×10^8 ft/hr^2

ρ = density of fluid (lb/ft^3)

Equation A-1 can be reduced to the Darcy equation in the form:

$$\frac{\Delta P}{L} = \frac{0.0216 f\, Q^2}{d^5} \qquad \text{A-2}$$

where:

Q = flow rate (gal/min)

d = tube inside diameter (in)

Equation A-1 shows that the tube size greatly affects the pressure drop within the tube. Some fluids, because of their higher pressure drops, require larger tube sizes than water.

The shell-side pressure drop can be found by using the following equation from D. Q. Kern.

$$\Delta P = \frac{f\ G_{max}^2\ D_s\ (N_{baf} + 1)}{2\ g\rho\ \ D_o\ 144} \quad \text{(psi)} \qquad \text{A-3}$$

where:

G_{max} = maximum flow rate through shell side ($lb/hr \cdot ft^2$)

D_s = shell diameter (ft)

N_{baf} = number of baffles within heat exchanger

D_o = tube outside diameter (ft)

f = friction factor

= $0.0014 + 0.125/Re'^{0.32}$

Re' = $G_{max} D_o / \rho$

Cost

In some applications, more expensive fluids can be competitive with less costly ones. In order to determine the relative cost of a heat transfer fluid, the volume of fluid required for a particular application must be known. For some applications (such as domestic hot water heating) the amount of heat transfer fluid required will be small since the collector area needed is small. In traced tank systems more costly fluids can be used if their other properties are desirable.

Table A-1 shows the 1978 costs of many heat transfer fluids in single 55-gallon drum quantities. Note for the glycol solutions that the final costs will generally be lower, since a 100-percent solution of the glycols is not necessary. Thus Mobiltherm light and the glycols are the least expensive heat transfer fluids for initial installation, while the silicone fluids are the most expensive.

There are other costs besides those of the initial fillup. Periodic maintenance and inhibitor addition, if needed, can add to the total cost of the fluid over a specific time period. Where inadequate corrosion and freeze protection might lead to collector failure, this additional cost must be considered. Also, more viscous fluids will require higher flow rates and increased pumping costs. Thus the total investment in fluid over a given time period is equal to the sum of the initial cost of the fluid plus any additional costs of added fluid or inhibitor, increased pumping costs, maintenance, cost of replaced parts needed because of inadequate freeze or corrosion protection, or cost of reserve draindown or expansion tanks needed for some fluids.

Table A-1. Initial Fillup Cost of Heat Transfer Fluids

Fluid	Cost per Gallon (Single 55-gallon drum quantities)	Manufacturer
Water	--	--
100% Ethylene Glycol	2.56	Union Carbide
100% Propylene Glycol	2.45	Union Carbide
100% Diethylene Glycol	2.82	Union Carbide
100% Triethylene Glycol	3.70	Union Carbide
100% Ucar[a] Thermofluid (Ethylene glycol & inhibitors)	3.81	Union Carbide
100% Ucar Foodfreeze (Propylene Glycol & inhibitors)	3.63	Union Carbide
100% Dowtherm[b] SR-1 (Ethylene Glycol & inhibitors)	3.65	Dow Chemical
100% Dowfrost[b] (Propylene Glycol & inhibitors)	3.45	Dow Chemical
Mobiltherm[c] Light	1.29	Mobil Oil
SF-96(50) (Silicone)	14.00	General Electric
Q2-1132 (Silicone)	23.00	Dow Corning
Dowtherm J	4.50	Dow Chemical
Therminol[d] 44	7.65	Monsanto
55	2.80	Monsanto
60	6.80	Monsanto
Sun-Temp[e]	3.50	Resource Technology Corporation

[a] Ucar is a trademark of Union Carbide Corporation.
[b] Dowtherm and Dowfrost are trademarks of Dow-Chemical Corporation.
[c] Mobiltherm is a trademark of Mobil Oil Corporation.
[d] Therminol is a trademark of Monsanto Company.
[e] Sun-Temp is a trademark of Resource Technology Corporation.

Toxicity

The toxicity of a heat transfer fluid can greatly affect the design and operation of a double-loop flat plate collector system. Most plumbing codes require that double walls or vented surfaces separate a toxic fluid from potable water supplies. The possibility of poisonous fumes escaping from the heat transfer fluid must also be considered. These problems require the use of different heat exchangers, which transfer heat less optimally than those that operate without a toxic fluid. The following discussion describes the toxicity of the heat transfer fluids studied. The information was obtained from the manufacturers.

In a discussion of toxicity the following definitions (from United States Codes Annotated, 1974) are useful.

A hazardous substance is any substance or mixture of substances which:

- Is toxic
- Is corrosive (will cause destruction of living tissue by chemical action)
- Is an irritant
- Is a strong sensitizer
- Is flammable or combustible
- Generates pressure through decomposition, heat, or other means.

A toxic substance is any substance that has the capacity to produce injury or illness to man through ingestion, inhalation, or absorption through any body surface.

A highly toxic substance is any substance that produces death within 14 days in half or more than half of a group of ten or more laboratory white rats, each weighing between 200 and 300 grams, at a single dose of 50 milligrams or less per kilogram of body weight when orally administered, or when inhaled continuously for a period of 1 hour or less at an atmospheric concentration of 200 parts per million by volume or less of gas or vapor, or 2 milligrams per liter by volume or less of dust or mist.

LD_{50} refers to the quantity of chemical substance that kills 50 percent of dosed animals within 14 days. Dosage is expressed in grams or milliliters per kilogram of body weight.

Single dose (acute) oral LD_{50} refers to the quantity of substance which kills 50 percent of dosed animals within 14 days when administered orally in a single dose.

Because the primary hazard in using heat transfer fluids is the possibility that the heat transfer fluid may leak into a potable water supply and be ingested, acute oral toxicity is the primary concern in this section. Table A-2 lists the LD_{50} values for selected fluids for

Table A-2. Acute Oral Toxicities of Heat Transfer Fluids

Fluid	LD_{50}
Water	--
100% Ethylene Glycol (No inhibitors)	8.0
100% Propylene Glycol (No inhibitors)	34.6
100% Diethylene Glycol (No inhibitors)	30.
100% Triethylene Glycol (No inhibitors)	30.
100% Dowtherm SR-1	4.
Mobiltherm Light	20.
SF-96(50) (Silicone)	50
Q2-1132 (Silicone)	50
Dowtherm J	1.1
Therminol 44	13.5
Therminol 55	15.8
Therminol 60	13.0
Sun-Temp	No test information available

acute oral toxicity. No substance listed is highly toxic according to the preceding definition, but several are quite toxic. Dowtherm J is the most toxic fluid listed in Table A-2, with the ethylene glycol mixture second. The least toxic fluids are silicone fluids, Sun-Temp, and propylene glycol. (Propylene glycol is routinely used in the food industry.)

Flammability

The possibility of the heat transfer fluid being a fire hazard was considered. In a discussion of the flammability of a heat transfer fluid the following definitions are useful.

> Boiling point -- the temperature at which the vapor pressure of a liquid equals the absolute external pressure at the liquid vapor interface.
>
> Flash point -- the lowest temperature at which a combustible vapor above a liquid ignites and burns when ignited momentarily in air.
>
> Fire point -- the lowest temperature at which a combustible vapor flashes and burns continuously.
>
> Self-ignition point -- the temperature at which self-sustained ignition and combustion in ordinary air take place independent of a heating source.
>
> Extremely flammable -- any substance that has a flash point at or below 20°F as determined by the TOCT (Togliabue Open Cup Tester).
>
> Flammable -- any substance that has a flash point between 20°F and 80°F as determined by the TOCT.
>
> Combustible -- any substance that has a flash point between 80°F and 150°F as determined by the TOCT.

Table A-3 lists the fluids studied and their boiling or flash points, whichever were supplied by the manufacturers. None of the fluids listed are extremely flammable or flammable. Only Dowtherm J is combustible, with a flash point of 145°F. With the exception of the silicone fluids, Sun-Temp, and Therminol 44, most of the fluids have flash points below possible staganation temperatures.

The HUD Minimum Property Standards for FHA eligibility, according to Kauffman, preclude the use of fluids whose flash points are not at least 100°F higher than the highest temperature to which they might be exposed. Thus the use of fluids with low flash points is limited unless adequate safeguards limit the exposure of these fluids to high temperatures and exposure to the atmosphere.

Table A-3. Flammability of Heat Transfer Fluids

Fluid	Boiling Point °F	Flash Point, °F (Cleveland Open Cup)
Water	212	--
100% Ethylene Glycol	388	240
50% Ethylene Glycol	225	
100% Propylene Glycol	370	225
100% Diethylene Glycol	475	290
100% Triethylene Glycol	550	330
100% Dowtherm SR-1	325	240
50% Dowtherm SR-1	230	
100% Dowfrost	--	214
Mobiltherm Light	250	
SF-96(50)		600
Q2-1132		450
Dowtherm J		145
Therminol 44	425	405
Therminol 55	600	355
Therminol 60	650	310
Sun-Temp	500	310

Corrosion

Butt and Popplewell state that general corrosion is usually slow in most systems but that localized corrosion is the prime cause for corrosion problems in flat plate collector systems. According to Popplewell, the four basic types of localized internal corrosion that can be affected by the heat transfer fluid are: (1) galvanic, (2) pitting, (3) crevice, and (4) erosion.

Galvanic corrosion occurs when two dissimilar metals are joined together in an electrolyte (a fluid that conducts electricity, such as an aqueous solution). Depending on the type of metals in contact, corrosion can occur quite rapidly at the interface. This problem can be avoided by separating any dissimilar metals in an electrolytic solution with insulating couplings.

Pitting corrosion is characterized by rapid localized metal loss which leads to perforation of metals in uninhibited aqueous solutions. For aluminum, the presence of chloride ions in the heat transfer fluid will aggravate this type of corrosion. Metal ions (copper and iron) will cause pitting to begin on aluminum surfaces. Steel is also susceptible to pitting corrosion in aqueous heat transfer fluids with chloride ions.

Crevice corrosion is similar to pitting corrosion in that rapid metal loss occurs in localized areas (inside crevices). Crevices can occur in blockages within internal channels or gaskets through which the heat transfer fluid passes. Aluminum and carbon steel are more susceptible to this form of corrosion in aqueous environments. This problem can be reduced by eliminating possible crevices by proper design.

Erosion Corrosion is caused by the joint action of corrosion coupled with mechanical removal of the protective product film. It occurs under high velocity or turbulent liquid flow conditions. Partial obstructions within the fluid channel can cause localized high velocities and enhanced corrosion. Aluminum, copper, and steel are all subject to this form of corrosion. According to Popplewell, a maximum velocity of 2 feet per second is considered relatively safe if the system is relatively free of abrasions.

General Wastage

Most of the fluid manufacturers show that the general wastage of common engineering materials by their fluids is small. Table A-4 shows several examples of general wastage of metallic surfaces by different fluids. Little is known at present of the possibilities of localized corrosion by the non-aqueous solutions.

Table A-4. General Corrosion of Various Metals by Heat Transfer Fluids

Metal	Silicone (Q2-1132), mg/cm^2	50% Propylene Glycol, mg/cm^2 per day
Aluminum	0.01 Bright	0.25
Cast Iron	0.01 Bright	--
Steel	0.01 Bright	0.002
Copper	0.02 Medium Stain	0.124

Silicone humidified fluid corrosion test results obtained as per SAE xj 1705 (from Dow Corning Form No. 22-380A-76).

Vapor Pressure

Under zero flow conditions within the collectors, temperatures in excess of 300°F are possible. For aqueous solutions the vapor pressure under stagnation conditions can reach several atmospheres. Some collectors cannot withstand these pressures. Figure A-5 shows the absolute vapor pressure versus temperature for several of the fluids. The vapor pressures of the fluids are quite low, even under zero flow conditions, except for the aqueous solutions and Dowtherm J.

Freeze Protection

One of the major drawbacks of using water as a heat transfer fluid is its high freezing temperature. In the continental United States, few locations have had no recorded below-freezing temperatures.

Antifreeze solutions have been commonly added to water to lower its freezing temperature. In some cases these solutions can retard the expansivity of the water and create a slush that will not rupture the fluid vessel. Most nonaqueous fluids do not expand upon freezing and thus will reduce the risk of damaged piping.

Because some fluids become so viscous that their freezing temperatures are not easily measured, the pour point temperatures of the fluids are used as their lower operating limits. The pour point temperature is the temperature of the fluid at which it fails to flow when the container is tilted to horizontal and held for 5 seconds.

Freeze protection temperatures can best be obtained from the manufacturer for the particular fluid in question.

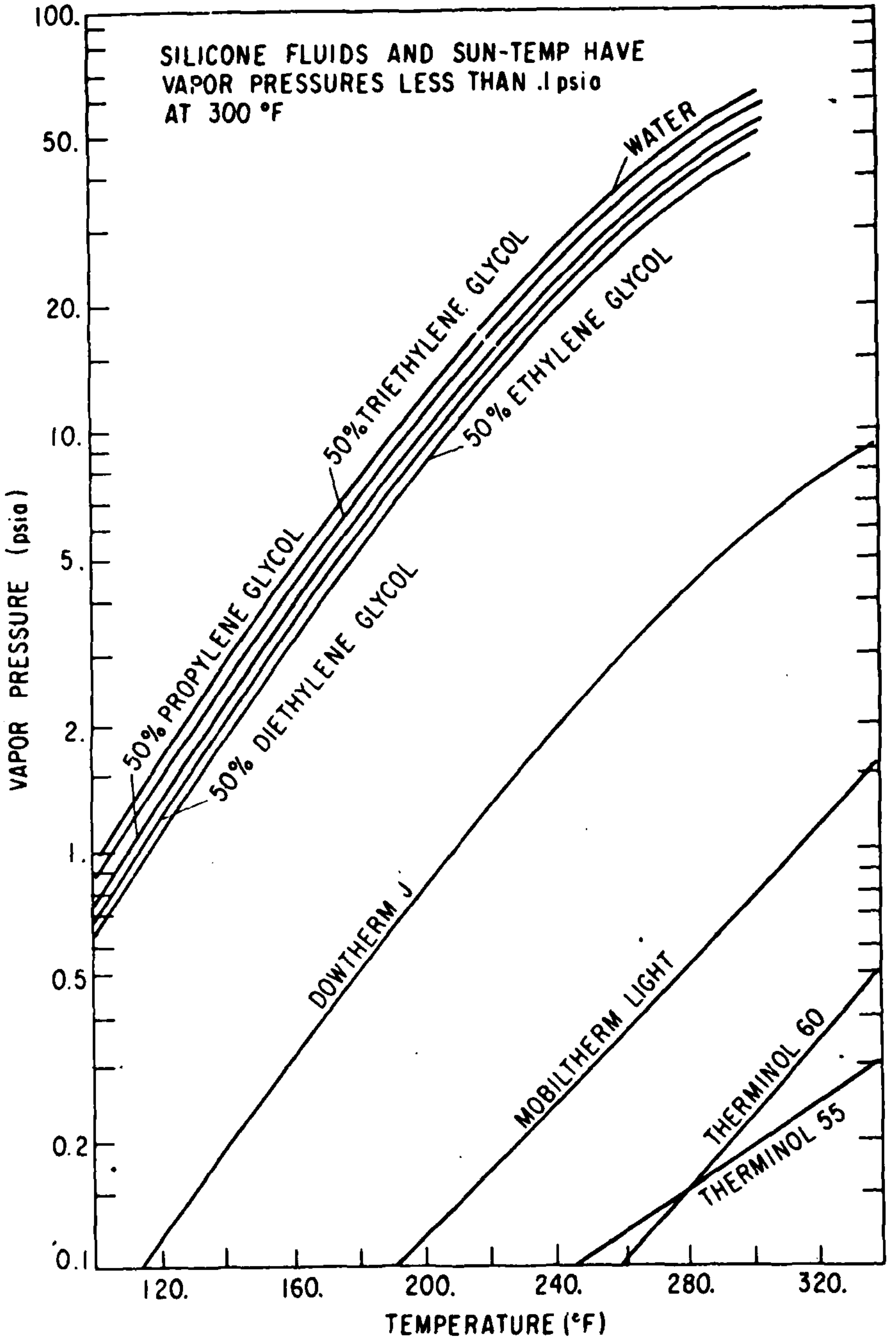

Figure A-5. Vapor Pressure of Heat Transfer Fluids Versus Temperature

APPENDIX C

HNDTR-80-45-SP

Economic Trade-off Analysis

for

Regional Petroleum Reserve Program

June 19, 1980

Prepared For
U.S. Army Corps of Engineers
Huntsville, Alabama

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ABSTRACT

This study identifies the pertinent economic factors associated with the purchase/lease alternatives concerning storage facilities for residual No. 6 fuel oil in the Northeastern United States.

An equivalent annual worth comparison is utilized which builds upon the double-declining balance method of depreciation, with an appropriate switch over to straight line depreciation for the lease alternative. The purchase alternative is a combination of initial investment and capital recovery factor for the appropriate interest rate, salvage value, and lifetime.

This study found the lease alternative superior to the purchase alternative for every case when the government interest rate equals the contractor interest rate. Included are 80 tables for varying interest rates between 5 and 25 percent, from which a decision can be made to select the appropriate conditions for the case under consideration.

ECONOMIC TRADE-OFF ANALYSIS

1.0. INTRODUCTION

This report studies the economic factors affecting a decision concerning the purchase or lease of facilities to store residual No. 6 fuel oil in aboveground tanks at a site in the Northeastern United States.

The decision on whether the government should buy (build) or lease the dock/terminal and storage facilities for the Regional Petroleum Reserve Program (RPR) is essentially an economic one. There are a number of reasons why the government should consider leasing the facilities. Among these are:

a. It may be less expensive. For an industrial firm, this is generally not true. However, in a situation where the lessee (the government) is not subject to taxation, nor concerned with profits, and the lessor is concerned with taxes and profits, it may in fact turn out to be less expensive. Only a thorough economic analysis can establish which is the best alternative.

b. The government can avoid tying up capital that can be utilized more profitably in other ways. Instead of laying out the capital when the facility is acquired, the government makes its payments as the facility is utilized.

c. The day-to-day concerns about maintenance, repair, protection against loss and destruction, obsolescence, deterioration, and replacement become the worries of the lessor.

1.1. ASSUMPTIONS

a. The present study is based on the conceptual design and cost estimates produced by Hallanger Engineers, Inc. of Baton Rouge, Louisiana, for the Department of Energy, Strategic Petroleum Reserve Office. The design is based on facilities to store 10 million barrels of residual No. 6 fuel oil in aboveground tanks at a site in the Northeastern United States. The facilities include a complete marine terminal designed to receive or ship products from barges or tankers up to 38,000-dwt, distribution pipelines between the marine terminal and the tank farm, and the tank farm itself. The specific details of the design itself are not pertinent to the present study and are available in the DOE report [1].

b. The salvage value of the facilities considered in this study is assumed to be zero. This is based on the concept that considers the facilities in need of complete refurbishment at the end of

the 20-year lifetime. Furthermore, technical obsolescence of the facilities at some point prior to the projected 20-year lifetime would incur a sunk cost equal to the salvage value which can be avoided by the assumption of zero salvage value. To test the validity of the assumption a case using a 10 percent assumed salvage value was run and found to have negligible effect on the results.

c. This analysis is based on 1980 dollars, with no adjustments for inflation or other economic conditions.

d. Operating and maintenance costs are excluded from this analysis, since these costs will undoubtedly be the same for the purchase or lease option. Should the purchase option be pursued, it is assumed the facility will be operated by an independent government contractor.

e. The depreciation method selected is one considered to be most advantageous to the contractor. It is the double-declining balance method, with the option of converting to the straight line method under the conditions described in paragraph 4.2. Depreciation is a consideration only for the lease option, since government built/owned facilities are not depreciable.

1.2. DEFINITIONS

Following are the definitions of some of the terms used in this study.

a. Interest Rate - Rate of gain received from an investment or rental amount charged by financial institutions for the use of money.

b. Value - The worth that a person attaches to an object or a service. The value of an object is not inherent in the object but is inherent in the regard that a person has for it.

c. Utility - The power to satisfy human wants. The utility that an object has for a person is the satisfaction he desires from it. Value is an appraisal of utility in terms of a medium of exchange.

d. Fixed Cost - That group of costs involved in an activity whose total will remain relatively constant throughout the range of operational activity. Fixed costs are made up of such things as depreciation, some maintenance, taxes, insurance, lease rentals, and interest on invested capital.

e. Variable Cost - That group of costs that vary in some relationship to the level of operational activity.

f. Depreciation - Lessening in value of a physical asset with the passage of time. Depreciation may be physical (wearing out) or functional (change in the demand for the services it can render) [2, p. 148].

g. Useful Life - That period of time which the Internal Revenue Service recognizes as appropriate for depreciating a capital asset.

h. Economic Life - That period of time for which an asset has utility for the investor.

i. Capital Recovery Plus Return - Capital invested in an asset is recovered in the form of income derived from services rendered by the asset, plus a fair return upon investment [3, p. 36].

j. Opportunity Loss - Alternative opportunities for investing which are foregone in order to invest in the present asset.

k. Straight-Line Method of Depreciation - Assumes that the value of an asset decreases at a constant rate [4, p. 331].

l. Double-Declining Balance Method of Depreciation - Assumes the asset decreases in value at twice the straight-line depreciation rate [4, p. 334].

m. Capital Recovery Factor - Provides a uniform series of end-of-period payments that are equivalent to a present single sum of money [5, p. 16].

2.0 SELECTION OF INTEREST RATES

A serious problem in the economic analysis of lease-buy situations for the government concerns the appropriate interest rate to use in the analysis. There are actually two different interest rates of concern:

a. Cost of money to the government, and

b. Cost of money to the lessor.

In government, money is obtained either by taxation or borrowing in the open money markets (long- and short-term Treasury bills and bonds). There are at least three different criteria that can be used in selecting an appropriate government interest rate to be used in the analysis:

(1) Cost to the government to borrow money (i.e., current rate on Treasury notes, bills and bonds).

(2) Governmental opportunity cost (i.e., rate of return the government could get if it put the capital into some other project).

(3) Taxpayers opportunity cost (i.e., what is a reasonable rate of return that the taxpayer could get if the money had not been taken by the government in the form of taxes for the general good).

The rate for the first method can be obtained from the current money markets. Recently, these rates have fluctuated due to uncertainties in the financial world. Even though the rates have been as high as 15 percent in recent months, it is believed that a rate between 8 and 12 percent is a more reasonable figure.

The rate for the second method is more difficult to determine. Since the benefits to be derived from any governmental project are often highly subjective, it is almost impossible to calculate what the rate of return might be on a specific expenditure. From a practical viewpoint, the criteria of governmental lost-opportunity cost is not useful.

The third possible criteria is that of taxpayer opportunity costs. The government has a moral obligation to invest any taxes collected profitably or let the individual retain the money for investment in organizations of his own choice. It is economically undesirable to take money from a taxpayer with a 9 percent opportunity cost, for example, and spend it on a governmental project yielding 6 percent. It is our contention that the cost of capital should not be established by the opportunity cost of the organization, but rather by the opportunity cost of the investors in that organization (i.e., the taxpayers). The investment opportunities personally available to the taxpayers should serve as the basic guide to the government's cost of capital. Under current conditions these opportunities are in the range of 6-3/4 percent (Credit Unions and U.S. Savings Bonds) to 14 percent (Money Market Mutual Funds).

In the present study a base rate of 10 percent is recommended as the cost of capital to the government, since this is about the midpoint of the ranges of both criteria 1 and 3.

The second interest rate, or cost of capital rate, of concern is that used for the lessor. It is assumed that only major, well-established organizations would be in a position to acquire and lease out a major facility of this nature. Therefore, they should be in a

position to borrow (or lend) capital at the prevailing prime interest rate charged by major banks. Although the current prime rate can readily be obtained, there have been tremendous fluctuations of this rate in recent months. Since the annual lease rate that a lessor would need to charge is highly sensitive to his cost or acquiring capital, the analysis is based on exploring the effect of this rate over a range of 5 to 25 percent.

3.0. CAPITAL RECOVERY PLUS RETURN

Capital assets are purchased in the belief that they will earn more than they cost. One part of the prospective earnings is considered to be capital recovery. Capital invested in an asset is recovered in the form of income derived from the services rendered by the asset and from its sale at the end of its useful life. If the asset provided services valued at $800 per year during its five-year life, and if $1,000 was received from its sale at the end of five years, a total of $5,000 would be recovered.

A second part of the prospective earnings will be considered to be return. Since capital invested in an asset is ordinarily recovered piecemeal, it is necessary to consider the interest on the unrecovered balance as a cost of ownership. Thus, an investment in an asset is expected to result in income sufficient not only to recover the amount of the original investment, but also to provide for a return on the diminishing investment remaining in the asset at any time during its life. This gives rise to the phrase capital recovery plus return.

In this study, capital recovery is synonymous with depreciation, while return is directly related to the rate of interest under consideration. In economic terms the rate of return represents the percentage or rate of interest earned on the unrecovered balance of an investment. The unrecovered balance of an investment can be viewed as the portion of the initial investment that remains at the time being considered, minus depreciation.

4.0. DOUBLE-DECLINING BALANCE METHOD OF DEPRECIATION

The double-declining balance method of depreciation provides for rapid recovery of capital in the early years of an asset's life. Calculations for capital recovered for a given year, book value, etc., are based on a value which is twice the straight line depreciation method. This may be expressed as:

$$DDB = \frac{2}{\text{number of years of asset's life}}.$$

Consider the following example of double-declining balance depreciation:

First Cost = \$5,000   Life = 5 years
Salvage Value = \$1,000   Interest Rate = 6%

$$D = \frac{2}{5} = .4$$

End of Year	Book Value Factor $(1 - D)^x$	Depreciation Factor	Depreciation For Year (Col.3) times (First Cost)	Book Value End of Year	Return on Capital Unrecovered	Capital Recovered + Return
0	1.00000			5000		
1	.60000	.40000	2000	3000	300.00	2300.00
2	.36000	.24000	1200	1800	180.00	1300.00
3	.21600	.14400	720	1080	108.00	828.00
4	.12960	.08640	80	1000	64.80	144.80
5	.07776	.05184	0	1000	60.00	60.00

As shown above, under the double-declining balance method, calculations of depreciation for each year will not in general sum up to the total depreciable amount over the asset's life. Since the depreciable amount is all that is necessary to account for, depreciation should stop when the book value of the asset reaches the salvage value. Also, in the example the depreciation charge for the fourth year was first calculated to be (.0864) (\$5,000) = \$432. However, the book value at the beginning of the year was \$1,080, which is \$80 above the salvage value of \$1,000. Thus, the maximum depreciation charge remaining was \$1,080 - \$1,000 = \$80 for the fourth year, and no depreciation could be charged for the fifth year.

A quite different problem arises when the salvage value is zero or very small with respect to the first cost. In this situation the sum of annual depreciation charges over the asset's total life is less than the depreciable amount. In order to account for this, either of two procedures may be followed:

4.1 The depreciation charge for the last year of the asset's life may include all remaining unrecovered capital, i.e.,

$$\text{Depreciation}_{\text{nth year}} = (\text{Book Value}_{\text{beginning year n}}) - (\text{Salvage Value}).$$

This procedure is sufficient when the depreciation charge for the last year thus calculated is not too much larger than the depreciation charges for the immediately preceding years.

4.2 It is permissible to convert from the double-declining balance method to the straight line method at any year in the asset's life. It is advisable to convert at that year for which the depreciation under the straight line method exceeds the depreciation calculated under the double-declining balance method. This "switch-over" is always preferable from the standpoint of taxes, but the necessary calculations can become quite tedious. [6]

Consider the following example which illustrates the calculations for procedure 2:

First Cost = \$10,000 Life = 8 years
Salvage Value = \$100 Interest Rate = 6%

$$D = \frac{2}{8} = .25$$

End of Year	Book Value Factor $(1 - D)^x$	Double-Declining Balance Depreciation Factor	Double-Declining Balance Depreciation Charge	Straight Line Depreciation Calculation of Depreciation for Remaining Life	Actual Depreciation Charge	Book Value at End of Year	Return on Unrecovered Capital	Capital Recovered + Return
0	1.0000	---	---	---	---	10,000	---	---
1	.7500	.2500	2500	$\frac{10{,}000 - 100}{8} = 1238$	2500	7,500	600	3100
2	.5625	.1875	1875	$\frac{7{,}500 - 100}{7} = 1057$	1875	5,625	450	2325
3	.4219	.1406	1406	$\frac{5{,}625 - 100}{6} = 921$	1406	4,219	338	1744
4	.3164	.1055	1055	$\frac{4{,}219 - 100}{5} = 824$	1055	3,164	253	1308
5	.2373	.0791	791	$\frac{3{,}614 - 100}{4} = 766$	791	2,373	190	981
6	.1780	.0593	593	$\frac{2{,}373 - 100}{3} = 758$	758	1,615	142	900
7	.1335	.0445	445	$\frac{1{,}615 - 100}{2} = 758$	758	858	97	855
8	.1001	.0334	334	$\frac{858 - 100}{1} = 758$	758	100	51	809

PROCEDURE 2

5.0. BASES FOR COMPARISON PURPOSES

Each of the bases for comparison have their advantages and disadvantages. Even though each is mathematically equivalent, it is important that the advantages and disadvantages be individually recognized and taken into consideration.

5.1. PRESENT WORTH BASIS

The value today of a future sum of money at a specified interest rate is called the present-worth of the future sum. This can be applied to the estimates of all future cash flows, (e.g., annual rents, ownership costs, etc.) associated with a proposed project to find the present worth of the project for comparison purposes. This method works best in those cases where initial investments are large in comparison to future cash flows. A disadvantage is that small changes in the interest rate used in the calculations cause large changes in the results. Also, this method is somewhat cumbersome to use when comparing projects with different useful lifetimes.

5.2. EQUIVALENT ANNUAL AMOUNT BASIS

The basis of this comparison is associated with use of cost accounting, which considers costs on an annual basis, and therefore, treats depreciation as an annual cost. One advantage of the equivalent annual amount basis is that it conforms to commonly used accounting practices. A second advantage is that the period of time under consideration is always one year. The amounts determined are actually a summation of receipts and disbursements per unit of time. Since equivalent annual amounts are based on a common unit, they are easier to understand and compare. Since people tend to live "by the year" and tend to think in terms of annual disbursements and receipts, it seems logical to make economic comparisons on the basis of yearly periods. Because of these advantages and its general use in engineering activities, the equivalent annual amount basis of comparison should be favored over either the present-worth or the capitalized amount basis.

5.3. CAPITALIZED AMOUNT BASIS

The capitalized amount of a proposed investment at a specified interest rate is the equivalent uniform annual cost of the investment divided by the specified interest rate. It is usually very close in value to the present-worth and is best suited for evaluation of proposals with long useful lives and stable cash flows. The results are somewhat difficult to comprehend, especially when applied to short useful lives. Therefore, it is rarely applied to proposals involving periods of less than 30 or 40 years.

6.0. CAPITAL RECOVERY FACTOR

The following symbols are necessary for the development of the capital recovery factor:

i = interest rate per interest period.
n = number of interest periods.
P = present sum of money.
F = sum of money at the end of n periods from the present date that is equivalent to P with interest i.
A = end-of-period payment in a uniform series continuing for the coming n periods, the entire series equivalent to P at interest rate i.

If P is invested at interest rate i, the interest for the first year is iP and the total amount at the end of the first year is $P + iP = P(1 + i)$. The second year the interest on this is $iP(1 + i)$, and the amount at the end of the second year is $P(1 + i) + iP(1 + i) = P(1 + i)^2$. Similarly, at the end of the third year the amount is $P(1 + i)^3$; at the end of n years it is $P(1 + i)^n$.

This is the equation for the compound amount, F, obtainable in n years from a principal, P,

$$F = P(1 + i)^n. \tag{1}$$

If we express P in terms of F, i, and n,

$$P = F\left[\frac{1}{(1 + i)^n}\right]. \tag{2}$$

P may then be thought of as the principal that will give a required amount F in n years; in other words, P is the present worth of a payment of F, n years hence.

The expression $(1 + i)^n$ is called the <u>single payment compound amount factor</u>. Its reciprocal $1/(1 + i)^n$ is called the <u>single payment present worth factor</u>.

If A is invested at the end of each year for n years, the total amount at the end of n years will obviously be the sum of the compound amounts of the individual investments. The money invested at the end of the first year will earn interest for $(n - 1)$ years; its amount will thus be $A(1 + i)^{n-1}$. The second year's payment will amount to $A(1 + i)^{n-2}$; the third year's to $A(1 + i)^{n-3}$; and so on until the last payment, made at the end of n years, which has earned no interest. The total amount F is $A[1 + (1 + i) + (1 + i)^2 + (1 + i)^3 + . . . + (1 + i)^{n-1}]$.

$$F = A[1 + (1 + i) + (1 + i)^2 + \ldots + (1 + i)^{n-2} + (1 + i)^{n-1}]. \quad (3)$$

Multiplying both sides of the equation by (1 + i),

$$(1 + i)F = A[(1 + i) + (1 + i)^2 + (1 + i)^3 + \ldots + (1 + i)^{n-1} + (1 + i)^n] . \quad (4)$$

Subtracting equation (3) from equation (4)

$$iF = A[(1 + i)^n - 1] .$$

Then

$$A = F\left[\frac{i}{(1 + i)^n - 1}\right]. \quad (5)$$

A fund established to produce a desired amount at the end of a given period of time by means of a series of end-of-period payments throughout the period is called a sinking fund. The expression,

$$\frac{i}{(1 + i)^n - 1}$$

is called the sinking fund factor.

To find the uniform end-of-year payment, A, which can be secured for n years from a present investment, P, substitute equation (1) for F in equation (5):

$$A = F\left[\frac{i}{(1 + i)^n - 1}\right] = P(1 + i)^n\left[\frac{i}{(1 + i)^n - 1}\right]$$

$$= P\left[\frac{i(1 + i)^n}{(1 + i)^n - 1}\right]. \qquad (6)$$

This may also be expressed as

$$A = P\left[\frac{i}{(1 + i)^n - 1} + i\right] .$$

This expression,

$$\frac{i(1 + i)^n}{(1 + i)^n - 1}$$

is called the capital recovery factor. As shown by its identity with

$$\left[\frac{i}{(1 + i)^n - 1} + i\right] ,$$

it is always equal to the sinking fund factor plus the interest rate. When multiplied by a present debt (which, from the viewpoint of the lender, is a present investment), it gives the uniform end-of-year payment necessary to repay the debt (the lender's investment) in n years with interest rate i.

To simplify presentation, the capital recovery factor will be identified as $(^{APi - n})$, with appropriate values for i and n, in the subsequent material.

7.0. DATA

The cost estimates provided by Hallanger Engineers, Inc., were reviewed by personnel from the U.S. Army Engineer Division, Huntsville. It was determined that the report was a "worst case" type design and included items that most likely would not be required for actual construction and operation of the facility. Consequently, the Hallanger Estimate was revised by the U.S. Army Engineer Division, Huntsville, and it is these revised estimates that were utilized in this study.

The cost estimate was broken down into four modules as follows:

Module I - Storage Site Facilities
Module II - Dock/Terminal Facilities
Module III - Transfer Facilities, Dock to Storage Site
Module IV - Land Acquisition

The cost estimates provided are shown in Table I.

These cost estimates must now be restructured such that the modular costs are entirely complete. This restructuring is shown in Table II.

TABLE I

Cost Estimates

Storage Site Module	$187,547,490
Dock/Terminal Module	24,961,599
Transfer Module	4,626,531
SUBTOTAL I	$217,135,620
Contractor Overhead (15% of Subtotal I)	32,570,343
SUBTOTAL II	$249,705,963
Contractor Profit (10% of Subtotal II)	24,970,596
SUBTOTAL III	$274,676,559
Bond (1% of Subtotal III)	2,746,766
SUBTOTAL IV (Subtotal III plus Bond)	$277,423,325
Land Acquisition Module	6,130,000
TOTAL	$283,553,325

NOTE: The construction costs were based upon Huntsville and then adjusted for the East Coast area using a location adjustment factor of 1.17.

TABLE II

Modular Cost Estimates

Module I (Storage Site)	$239,620,051
Module II (Dock/Terminal)	31,892,187
Module III (Transfer)	5,911,087
SUBTOTAL I (Depreciable Assets)	$277,423,325
Module IV (Land Acquisition)	6,130,000
TOTAL	$283,553,325

7.1. DATA ANALYSIS

The primary objective of this study is to evaluate the economic tradeoffs which exist between the purchase and lease options concerning the proposed Regional Petroleum Reserve storage facilities in the Northeastern United states. The simplest comparison involves the evaluation of the two options on the basis of an equivalent annual cost comparison.

Cost to Purchase:

Assume:
- i = 10%
- n = 20 years
- Salvage value = 0
- Initial investment = $277,423,325
- Equivalent annual cost = initial investment (capital recovery factor) AP 10-20
  = $277,423,325 (.11746)
  = $32,586,040/yr.

Cost to Lease:

Assume:
- Government i = 10%
- Contractor i = 10%
- n = 20 years
- Depreciation = Straight line
- Salvage value = 0
- Initial investment = $277,423,325
- Equivalent annual cost = [initial investment (capital recovery factor) - depreciation value] AP 10-20
  = [277,423,325 (.11746) - 13,871,166]
  = $32,586,040 - $13,871,166
  = $18,714,874

Consequently, the lessor will not accept less than $18,714,978 to enter into a lease agreement with the government, based on the given assumptions.

Hence, the bounds for the buy vs. lease situation in terms of dollar cost to the government on the basis of equivalent annual cost with i = 10% are:

$$\$18,714,874 \leq \text{cost of lease} \leq \$32,586,040.$$

Consider now the effect of a 10% salvage value.

Cost to Purchase:

Assume:
$$
\begin{aligned}
i &= 10\% \\
n &= 20 \text{ years} \\
\text{Salvage value} &= \$27,742,332 \\
\text{Initial investment} &= \$277,423,325 \\
\text{Equivalent annual cost} &= [(\text{initial investment - salvage value}) \\
&\quad (\text{capital recovery factor})] + \\
&\quad (\text{salvage value})\ (\text{interest rate}) \\
&\qquad\qquad\qquad\qquad\qquad \text{AP 10-20} \\
&= (\$277,423,325 - 27,742,332)\ (\ .11746\ ) \\
&\quad + (27,742,332)\ (.10) \\
&= \$29,327,529 + \$2,774,233 \\
&= \$32,101,762
\end{aligned}
$$

Cost to Lease:

Assume:
$$
\begin{aligned}
\text{Government } i &= 10\% \\
\text{Contractor } i &= 10\% \\
n &= 20 \text{ years} \\
\text{Depreciation} &= \text{Straight line} \\
\text{Salvage value} &= \$27,742,332 \\
\text{Initial investment} &= \$277,423,325 \\
\text{Equivalent annual cost} &= [(\text{initial investment - salvage value}) \\
&\quad (\text{capital recovery factor})] - \\
&\quad \text{depreciation value} + (\text{salvage value}) \\
&\quad (\text{interest rate}) \\
&\qquad\qquad\qquad\qquad\qquad \text{AP 10-20} \\
&= (\$277,423,325 - \$27,742,332)\ (\ .11746\ ) \\
&\quad - 13,871,166 + 2,774,233 \\
&= \$18,230,596
\end{aligned}
$$

Hence, the bounds for the purchase vs. lease situation in terms of dollar cost to the government on the basis of equivalent annual cost with $i = 10\%$ and a salvage value of 10% with straight line depreciation are:

$$\$18,230,596 \leq \text{cost of lease} \leq \$32,101,762$$

It is noted that the lower and upper bound for this example are $484,278 less than those for the previous example. This $484,278 is the amount associated with the 10% salvage value. It is common to both the purchase and lease alternatives, and consequently has the same effect on each.

However, these examples may not be realistic because of the 10% interest rate and the straight line method of depreciation utilized for the lessor. Consequently, interest rates from 5% to 25% have been considered, together with the double-declining balance depreciation method, in the material contained in Appendix A. Appendix A material was generated with the computer code contained in Appendix B.

Computer Output Explanation:

Consider Table III as a typical example of the output associated with this economic evaluation. The portion of the analysis under consideration is given by the computer generated heading at the top of the page, which in this table is TOTAL. Immediately under this heading are six distinct items, which identify the pertinent parameters under consideration. The first item is the initial investment, which represents the total amount of funds involved in this portion of the project. Second is the salvage value of the project at the end of its useful lifetime. Third is the interest rate involved, which is designated as i in the equations. Fourth is the estimated lifetime of the asset, designated as n in the equations. Fifth is the capital recovery factor, which is calculated from the capital recovery equation, and is a function of i and n. Sixth is the equivalent annual cost, which represents the end-of-year cost for each year of the asset's lifetime.

The remaining portion of the table consists of five columns of information. Column 1 identifies the year of the asset's lifetime. Column 2 represents the end-of-the-year permissible depreciation amount for the asset under consideration, utilizing the double-declining balance method of depreciation. Column 3 is somewhat more complicated. The first eleven values in Column 3 represent the permissible end-of-the-year depreciation amount if the user switched from double-declining balance depreciation to straight line depreciation. However, the switch does not transpire, in this example, until year 11, at which time the depreciable amount becomes a constant for the remaining lifetime of the asset. The values bounded by the vertical lines indicate the values utilized in the calculation. Column 4 depicts the return realized on the unrecovered asset amount for a particular interest rate. This amount may be viewed as the interest charge for the use of the capital associated with this project. Finally, Column 5 provided the summation of the permissible depreciation amount plus Column 4. Thus, Column 5 identifies the summation of the initial investment recovered plus the return on the unrecovered investment.

TABLE III. Typical Computer Output

			TOTAL
INITIAL INVESTMENT	=	$	277423325.
SALVAGE VALUE	=	$	0.
INTEREST (%)	=		16.
LIFETIME (YEARS)	=		20.
CAPITAL RECOVERY FACTOR	=		.16867
EQUIVALENT ANNUAL COST	=	$	46792167.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	27742332.	13871166.	44387731.	72130063.
2	24968099.	13141105.	39948958.	64917057.
3	22471289.	12484050.	35954062.	58425351.
4	20224160.	11896565.	32358656.	52582817.
5	18201744.	11376090.	29122791.	47324535.
6	16381570.	10921047.	26210512.	42592082.
7	14743413.	10531009.	23589461.	38332873.
8	13269072.	10206978.	21230515.	34499586.
9	11942165.	9951804.	19107463.	31049628.
10	10747948.	9770862.	17196717.	27944665.
11	9673154.	9673154.	15477046.	25150199.
12	8705838.	9673154.	13929341.	23602495.
13	7835255.	9673154.	12381637.	22054790.
14	7051729.	9673154.	10833932.	20507086.
15	6346556.	9673154.	9286228.	18959381.
16	5711901.	9673154.	7738523.	17411677.
17	5140711.	9673154.	6190819.	15863972.
18	4626640.	9673154.	4643114.	14316268.
19	4163976.	9673154.	3095410.	12768563.
20	3747578.	9673154.	1547705.	11220859.

Realistic Cost to Lease Example:

Assume:
Government i = 10%
Contractor i = 16%
n = 20 years
Depreciation = double-declining
Salvage value = 0
Initial investment = $277,423,325

This analysis is not as straightforward as the previous. Observe that Table III provides the necessary values to assist in making our decision. The column entitled RETURN ON UNRECOVERED CAPITAL provides a year-by-year evaluation of the expected minimum return to the contractor if the contractor interest rate is 16 percent. Recall that this example assumes the government interest rate is 10 percent giving an equivalent annual cost of $32,586,040. Consequently, the contractor return on unrecovered capital exceeds the government purchase cost for the first three years, but is steadily decreasing after the third year.

Thus, it appears advantageous for the government to lease under these conditions. Note however, that in every case where the government i = contractor i ($i \leq 25\%$) it is a clear-cut decision in favor of leasing.

One additional situation requires consideration. That is, what conditions are necessary for the purchase alternative to be more favorable than the lease alternative? Obviously, the government interest rate would have to be considerably less than the contractor interest rate to offset the depreciation effect. There are a number of different combinations possible which are most easily acquired through computer manipulation. For illustration purposes, consider the following example:

Assume:
Government i = ?
Contractor i = 20%
n = 20 years
Depreciation = Straight line
Salvage value = 0
Initial investment = $277,423,325

$$\text{Equivalent annual cost} = [\$277,423,325 \overset{AP\ 20\text{-}20}{(\ .20536\ )} - \$13,871,166]$$
$$= \$56,971,654 - \$13,871,166$$
$$= \$43,100,488$$

We now go to Appendix A and search for an equivalent annual cost value $\leq$ $43,100,488. It is noted that an interest rate of 14% gives an equivalent annual cost of $41,887,038 while a 15% interest rate provides a value of $44,321,557. Thus, we see from this example that the difference in interest rate for the purchase vs. lease alternatives is approximately 6% for this example. This delta in interest rate between the purchase and

lease alternative will fluctuate around the 6% value depending upon the magnitude of the contractor interest rate.

Let us now consider a 10% salvage value for the previous example. The calculations become:

$$\text{Equivalent annual cost} = [(\$277{,}423{,}325 - 27{,}742{,}332)\left(\overset{\text{AP 20-20}}{.20536}\right) - 13{,}871{,}166 + 27{,}742{,}332\ (.20)]$$
$$= \$51{,}274{,}489 - \$13{,}871{,}166 + \$5{,}548{,}466$$
$$= \$42{,}951{,}789$$

Searching Appendix A for a value $\leq$ \$42,951,789, we find the appropriate interest rate to be 14% or less. Thus, whenever the contractor interest rate is 20%, while the government interest rate is 14% or less, it is more advantageous to purchase, considering straight line depreciation.

The calculations necessary to make a similar analysis considering double-declining balance and a salvage value are beyond the scope of this study.

8.0 CONCLUSIONS AND RECOMMENDATIONS

The purpose of this study was to evaluate the economic trade-offs which exist relative to the government purchase alternative versus the government lease alternative concerning storage facilities for No. 6 fuel oil in the Northeastern United States. The approach taken identified the parameters, and then provided a number of possible conditions which could occur. In particular, interest rates range from 5 to 25 percent, with an asset lifetime of 20 years. The asset salvage value is assumed to be zero.

The most advantageous method of depreciation for a contractor was selected, namely double-declining balance. This permits the evaluation to utilize the optimistic approach for comparison purposes.

The basis selected for evaluation of the two alternatives was equivalent annual cost. The material contained in Appendix A very clearly indicates that leasing is superior to the purchase alternative, from the government's viewpoint, when the interest rate is the same for the government and the contractor. This situation very clearly reflects the effect of depreciation upon economic analyses. Since the government does not depreciate assets, and does not pay taxes, the effect is very pronounced. It is not envisioned that the contractor will utilize a depreciation method which would be detrimental to his financial status. In most cases, the method of depreciation selected will be double-declining balance.

When the interest rates are different for each alternative, it is necessary to select the appropriate computer output for each, and make an individual comparison between the two alternatives. Consequently, it is not possible to recommend a particular course of action when the alternatives utilize differing interest rates.

This study was merely a starting point for a very complex situation. There are several other methods of depreciation which may be considered. Further, the capability of identifying a salvage value other than zero would be helpful. Also, the capability to consider non-integer interest rates may be necessary for some situations.

In economic decision situations of this type, it is frequently impossible to completely remove the human judgment element. Selection of interest rates falls into this category. Consequently, the availability of output for various conditions can be of immeasurable assistance in selecting the proper alternative.

REFERENCES

1. Department of Energy, Strategic Petroleum Reserve Office, "Detailed Conceptual Cost Estimates Base Case Northeast Regional Petroleum Reserve Tank Farm," 1980.

2. Grant, E. L., W. G. Ireson and R. S. Leavenworth, Principles of Engineering Economy, Sixth Edition, Ronald Press, New York, N. Y., 1976.

3. Canada, J. R., Intermediate Economic Analysis for Management and Engineering, Prentice-Hall, Inc., 1971.

4. Thuesen, H. G., W. J. Fabrycky and G. J. Thuesen, Engineering Economy, Fifth Edition, Prentice-Hall, Inc., 1977.

5. Stermole, F. J., Economic Evaluation and Investment Decision Methods," Second Edition, Investment Evaluations Corporation, Golden, Colorado, 1974.

6. U. S. Government Printing Office, "Depreciation," Publication 534 (Rev. Nov. 79), Stock Number 048-004-01656-7, Department of the Treasury, Internal Revenue Service, Washington, D. C., 20402, 1979.

APPENDIX A

Computer Code Outputs

TOTAL

```
INITIAL INVESTMENT          = $  277423323.
SALVAGE VALUE               = $          0.
INTEREST (%)                =            5.
LIFETIME (YEARS)            =           20.
CAPITAL RECOVERY FACTOR     =       .08024
EQUIVALENT ANNUAL COST      = $   22261166.
```

	DEPRECIATION		CAPITAL	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	27742332.	13871166.	13871166.	41613498.
2	24968099.	13141105.	12484049.	37452148.
3	22471289.	12484050.	11235645.	33706933.
4	20224160.	11896565.	10112080.	30336241.
5	18201744.	11376090.	9100872.	27302617.
6	16381570.	10921847.	8190785.	24572355.
7	14743413.	10531069.	7371707.	22115119.
8	13269072.	10206978.	6634536.	19903608.
9	11942165.	9951894.	5971082.	17913247.
10	10747948.	9772862.	5373974.	16121922.
11	9673154.	9673154.	4836577.	14509730.
12	8705838.	9673154.	4352919.	14026073.
13	7835255.	9673154.	3869262.	13542415.
14	7051729.	9673154.	3385604.	13058758.
15	6346556.	9673154.	2901946.	12575100.
16	5711901.	9673154.	2418289.	12091442.
17	5140711.	9673154.	1934631.	11607785.
18	4626640.	9673154.	1450973.	11124127.
19	4163976.	9673154.	967316.	10640469.
20	3747578.	9673154.	483658.	10156811.

TOTAL

INITIAL INVESTMENT	=	$	277423325.
SALVAGE VALUE	=	$	0.
INTEREST (%)	=		0.
LIFETIME (YEARS)	=		20.
CAPITAL RECOVERY FACTOR	=		.05718
EQUIVALENT ANNUAL COST	=	$	24187031.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	27742332.	13871166.	16645399.	44387731.
2	24968099.	13141105.	14980859.	39948958.
3	22471289.	12484050.	13482773.	35954062.
4	20224160.	11896555.	12134496.	32358657.
5	18201744.	11376090.	10921047.	29122791.
6	16381570.	10921047.	9828942.	26210512.
7	14743413.	10531069.	8846048.	23589461.
8	13269072.	10206978.	7961443.	21230515.
9	11942165.	9951804.	7165299.	19107463.
10	10747948.	9770862.	6448769.	17196717.
11	9673154.	9673154.	5803892.	15477046.
12	8705838.	9673154.	5223503.	14896657.
13	7835255.	9673154.	4643114.	14316267.
14	7051729.	9673154.	4062725.	13735878.
15	6346556.	9673154.	3482335.	13155489.
16	5711901.	9673154.	2901946.	12575100.
17	5140711.	9673154.	2321557.	11994711.
18	4626640.	9673154.	1741168.	11414321.
19	4163976.	9673154.	1160779.	10833932.
20	3747578.	9673154.	580389.	10253543.

TOTAL

```
INITIAL INVESTMENT         = $  277423325.
SALVAGE VALUE              = $         0.
INTEREST (%)               =           7.
LIFETIME (YEARS)           =          20.
CAPITAL RECOVERY FACTOR    =      .09439
EQUIVALENT ANNUAL COST     = $  2618680[illegible].
```

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	27742332.	13871166.	19419632.	47161964.
2	24968099.	13141105.	17477669.	42445768.
3	22471289.	12484050.	15729902.	38201191.
4	20224160.	11896565.	14156912.	34381072.
5	18201744.	11376096.	12741221.	30942965.
6	16381570.	10921047.	11467099.	27848669.
7	14743413.	10531009.	10320389.	25063802.
8	13269072.	10206978.	9288350.	22557422.
9	11942165.	9951804.	8359515.	20301680.
10	10747948.	9770862.	7523564.	18271512.
11	9673154.	9673154.	6771207.	16444361.
12	8705838.	9673154.	6094087.	15767240.
13	7835255.	9673154.	5416966.	15090120.
14	7051729.	9673154.	4739845.	14412999.
15	6346556.	9673154.	4062725.	13735878.
16	5711901.	9673154.	3385604.	13058758.
17	5140711.	9673154.	2708483.	12381637.
18	4626640.	9673154.	2031362.	11704516.
19	4163976.	9673154.	1354242.	11027395.
20	3747578.	9673154.	677121.	10350275.

TOTAL

```
INITIAL INVESTMENT        = $   277427325.
SALVAGE VALUE             = $          0.
INTEREST (%)              =            8.
LIFETIME (YEARS)          =           20.
CAPITAL RECOVERY FACTOR   =        .10185
EQUIVALENT ANNUAL COST    = $    28256178.
```

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	27742832.	13871166.	22193865.	49936197.
2	24968099.	13141105.	19974479.	44942578.
3	22471289.	12484050.	17977031.	40448320.
4	20224160.	11896565.	16179328.	36403488.
5	18201744.	11376090.	14561395.	32763140.
6	16381570.	10921047.	13105256.	29486826.
7	14743413.	10571069.	11794730.	26538143.
8	13269072.	10265970.	10615257.	23884329.
9	11942165.	9951864.	9553732.	21495896.
10	10747948.	9773862.	8598359.	19346307.
11	9673154.	9673154.	7738523.	17411676.
12	8705838.	9673154.	6964671.	16637824.
13	7835255.	9673154.	6190818.	15863972.
14	7051729.	9673154.	5416966.	15090120.
15	6346556.	9673154.	4643114.	14316268.
16	5711901.	9673154.	3869262.	13542415.
17	5140711.	9673154.	3095409.	12768563.
18	4626640.	9673154.	2321557.	11994711.
19	4163976.	9673154.	1547705.	11220858.
20	3747578.	9673154.	773853.	10447006.

TOTAL

```
INITIAL INVESTMENT         = $   277427325.
SALVAGE VALUE              = $           0.
INTEREST (%)               =             9.
LIFETIME (YEARS)           =            20.
CAPITAL RECOVERY FACTOR    =        .10955
EQUIVALENT ANNUAL COST     = $    30399746.
```

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	27742332.	13871166.	24968099.	52710431.
2	24968099.	13141105.	22471289.	47439388.
3	22471289.	12484050.	20224160.	42695449.
4	20224160.	11696565.	18201744.	38425905.
5	18201744.	11376090.	16381570.	34583314.
6	16381570.	10921047.	14743413.	31124983.
7	14743413.	10531069.	13269072.	28012485.
8	13269072.	10206978.	11942165.	25211236.
9	11942165.	9951804.	10747948.	22690113.
10	10747948.	9776862.	9673154.	20421102.
11	9673154.	9673154.	8705838.	18378992.
12	8705838.	9673154.	7835254.	17508408.
13	7835255.	9673154.	6964671.	16637824.
14	7051729.	9673154.	6094087.	15767241.
15	6346556.	9673154.	5223503.	14896657.
16	5711901.	9673154.	4352919.	14026073.
17	5140711.	9673154.	3482336.	13155489.
18	4626640.	9673154.	2611752.	12284905.
19	4163976.	9673154.	1741168.	11414322.
20	3747578.	9673154.	870584.	10543738.

TOTAL

INITIAL INVESTMENT	= $	277423325.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	10.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.11746
EQUIVALENT ANNUAL COST	= $	32586040.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	27742332.	13871166.	27742332.	55484664.
2	24968099.	13141105.	24968099.	49936198.
3	22471289.	12484050.	22471289.	44942578.
4	20224160.	11896565.	20224160.	40448321.
5	18201744.	11376090.	18201744.	36403489.
6	16381570.	10921047.	16381570.	32763140.
7	14743413.	10531009.	14743413.	29486826.
8	13269072.	10206978.	13269072.	26538144.
9	11942165.	9951804.	11942165.	23884329.
10	10747948.	9770862.	10747948.	21495897.
11	9673154.	9673154.	9673154.	19346307.
12	8705838.	9673154.	8705838.	18378992.
13	7835255.	9673154.	7739523.	17411677.
14	7051729.	9673154.	6771208.	16444361.
15	6346556.	9673154.	5803892.	15477046.
16	5711901.	9673154.	4836577.	14509731.
17	5140711.	9673154.	3869262.	13542415.
18	4626640.	9673154.	2901946.	12575100.
19	4163976.	9673154.	1934631.	11607785.
20	3747578.	9673154.	967316.	10640469.

TOTAL

```
INITIAL INVESTMENT        = $   277423320.
SALVAGE VALUE             = $           0.
INTEREST (%)              =            11.
LIFETIME (YEARS)          =            20.
CAPITAL RECOVERY FACTOR   =        .12558
EQUIVALENT ANNUAL COST    = $    34837610.
```

YEAR	DEPRECIATION ($) DOUBLE DECLINING BALANCE	STRAIGHT LINE	CAPITAL ($) RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	27742332.	13871166.	30516565.	58258897.
2	24968099.	13141105.	27464909.	52433007.
3	22471289.	12484050.	24718418.	47189707.
4	20224160.	11896565.	22246576.	42470737.
5	18201744.	11376090.	20021919.	38223663.
6	16381570.	10921047.	18019727.	34401297.
7	14743413.	10531009.	16217754.	30961167.
8	13269072.	10206975.	14595979.	27865051.
9	11942165.	9951804.	13136381.	25078546.
10	10747948.	9776862.	11822743.	22570691.
11	9673154.	9673154.	10640469.	20313622.
12	8705838.	9673154.	9576422.	19249576.
13	7835255.	9673154.	8512375.	18185529.
14	7051729.	9673154.	7448328.	17121482.
15	6346556.	9673154.	6384282.	16057435.
16	5711901.	9673154.	5320235.	14993388.
17	5140711.	9673154.	4256188.	13929342.
18	4626640.	9673154.	3192141.	12865295.
19	4163976.	9673154.	2128094.	11801248.
20	3747578.	9673154.	1064047.	10737201.

TOTAL

INITIAL INVESTMENT = $ 277423320.
SALVAGE VALUE = $ 0.
INTEREST (%) = 12.
LIFETIME (YEARS) = 20.
CAPITAL RECOVERY FACTOR .13388
EQUIVALENT ANNUAL COST = $ 37141096.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	27742332.	13871166.	33290798.	61033130.
2	24968099.	13141105.	29961719.	54929817.
3	22471289.	12484550.	26965547.	49436836.
4	20224160.	11860565.	24268992.	44493153.
5	18201744.	11376090.	21842093.	40043837.
6	16381570.	10921047.	19657884.	36039454.
7	14743413.	10531009.	17692095.	32435508.
8	13269072.	10206975.	15922886.	29191958.
9	11942165.	9951364.	14330598.	26272762.
10	10747948.	9770882.	12897536.	23645486.
11	9673154.	9673154.	11607784.	21280938.
12	8705838.	9673154.	10447006.	20120160.
13	7835255.	9673154.	9286226.	18959381.
14	7051729.	9673154.	8125449.	17798603.
15	6346556.	9673154.	6964671.	16637825.
16	5711901.	9673154.	5803892.	15477046.
17	5140711.	9673154.	4643114.	14316268.
18	4626640.	9673154.	3482336.	13155489.
19	4163976.	9673154.	2321557.	11994711.
20	3747578.	9673154.	1160779.	10833932.

TOTAL

INITIAL INVESTMENT = $ 277423325.
SALVAGE VALUE = $ 0.
INTEREST (%) = 13.
LIFETIME (YEARS) = 20.
CAPITAL RECOVERY FACTOR = .14235
EQUIVALENT ANNUAL COST = $ 39492263.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	27742332.	13871166.	36065031.	63807363.
2	24968099.	13141105.	32459528.	57427627.
3	22471289.	12484050.	29212676.	51683965.
4	20224160.	11896565.	26291408.	46515569.
5	18201744.	11376090.	23662268.	41864012.
6	16381570.	10921047.	21296041.	37677611.
7	14743413.	10531009.	19166437.	33909850.
8	13269072.	10206978.	17249793.	30518865.
9	11942165.	9951804.	15524814.	27466979.
10	10747948.	9770862.	13972333.	24720281.
11	9673154.	9673154.	12575100.	22248253.
12	8705839.	9673154.	11317590.	20990743.
13	7835255.	9673154.	10060080.	19733233.
14	7051729.	9673154.	8802570.	18475724.
15	6346556.	9673154.	7545060.	17218214.
16	5711901.	9673154.	6287550.	15960704.
17	5140711.	9673154.	5030040.	14703194.
18	4626640.	9673154.	3772530.	13445684.
19	4163976.	9673154.	2515020.	12188174.
20	3747578.	9673154.	1257510.	10930664.

TOTAL

INITIAL INVESTMENT	= $	277423325.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	14.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.15099
EQUIVALENT ANNUAL COST	= $	41887036.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	27742332.	13871166.	38839265.	66581597.
2	24968099.	13141105.	34955338.	59923437.
3	22471289.	12484050.	31459805.	53931094.
4	20224160.	11896555.	28313824.	48537985.
5	18201744.	11376090.	25482442.	43684186.
6	16381570.	10921047.	22934193.	39315768.
7	14743413.	10531009.	20640778.	35384191.
8	13269072.	10270978.	18576700.	31845772.
9	11942165.	9951864.	16719031.	28661195.
10	10747948.	977[illegible].	15047128.	25795076.
11	9673154.	9673154.	13542415.	23215568.
12	8705838.	9673154.	12188174.	21861327.
13	7835255.	9673154.	10933932.	20507086.
14	7051729.	9673154.	9479691.	19152844.
15	6346556.	9673154.	8125449.	17798603.
16	5711901.	9673154.	6771208.	16444362.
17	5140711.	9673154.	5416966.	15090120.
18	4626640.	9673154.	4062725.	13735879.
19	4163976.	9673154.	2708483.	12381637.
20	3747578.	9673154.	1354242.	11027396.

TOTAL

INITIAL INVESTMENT = $ 277427365.
SALVAGE VALUE = $ 0.
INTEREST (%) = 15.
LIFETIME (YEARS) = 20.
CAPITAL RECOVERY FACTOR = .15976
EQUIVALENT ANNUAL COST = $ 44321057.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	27742732.	13871166.	41613498.	69355830.
2	24968459.	13141105.	37452143.	62420247.
3	22471099.	12484035.	33706933.	56178222.
4	20224160.	11896565.	30336240.	50560401.
5	18201744.	11378077.	27302616.	45504361.
6	16381570.	10921047.	24572355.	40953925.
7	14743413.	10531099.	22115119.	36858532.
8	13269072.	10270972.	19903608.	33172679.
9	11942165.	9951064.	17913247.	29855412.
10	10747948.	9775862.	16121922.	26869871.
11	9673154.	9673154.	14509730.	24182884.
12	8705838.	9673154.	13058757.	22731911.
13	7835255.	9673154.	11607784.	21280938.
14	7051729.	9673154.	10156811.	19829965.
15	6346556.	9673154.	8705839.	18378992.
16	5711901.	9673154.	7254866.	16928019.
17	5140711.	9673154.	5803893.	15477046.
18	4626640.	9673154.	4352920.	14026073.
19	4163976.	9673154.	2901947.	12575100.
20	3747578.	9673154.	1450974.	11124127.

TOTAL

```
INITIAL INVESTMENT         = $   277423325.
SALVAGE VALUE              = $           0.
INTEREST (%)               =            16.
LIFETIME (YEARS)           =            20.
CAPITAL RECOVERY FACTOR    =         .16867
EQUIVALENT ANNUAL COST     = $    46792167.
```

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	27742332.	13871166.	44387731.	72130063.
2	24968099.	13141105.	39948958.	64917057.
3	22471289.	12484050.	35954062.	58425351.
4	20224160.	11896565.	32358656.	52582817.
5	18201744.	11376090.	29122791.	47324535.
6	16381570.	10921047.	26210512.	42592082.
7	14743413.	10531009.	23589461.	38332873.
8	13269072.	10206978.	21230515.	34499586.
9	11942165.	9951804.	19107463.	31049628.
10	10747948.	9770862.	17196717.	27944665.
11	9673154.	9673154.	15477045.	25150199.
12	8705838.	9673154.	13929341.	23602495.
13	7835255.	9673154.	12381637.	22054790.
14	7051729.	9673154.	10833932.	20507086.
15	6346556.	9673154.	9286228.	18959381.
16	5711901.	9673154.	7738523.	17411677.
17	5140711.	9673154.	6190819.	15863972.
18	4626640.	9673154.	4643114.	14316268.
19	4163976.	9673154.	3095410.	12768563.
20	3747578.	9673154.	1547705.	11220859.

TOTAL

INITIAL INVESTMENT	= $	277423525.
SALVAGE VALUE	= $	0.
INT COST (%)	=	17.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.17769
EQUIVALENT ANNUAL COST	= $	49295449.

YEAR	DEPRECIATION ($) DOUBLE DECLINING BALANCE	STRAIGHT LINE	CAPITAL ($) RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	27743532.	13871166.	47161965.	74904297.
2	24969199.	13141165.	42445768.	67413867.
3	22471289.	12414650.	38201191.	60672480.
4	20224160.	11696565.	34381073.	54605233.
5	18201744.	11370096.	30942966.	49144710.
6	16381570.	10921047.	27848669.	44230239.
7	14743413.	10521609.	25063802.	39807215.
[illegible]	13269072.	[illegible]	22557422.	35826494.
[illegible]	11942165.	[illegible]	20301680.	32243845.
10	10747948.	9773862.	18271512.	29019460.
11	9673154.	9673154.	16444361.	26117515.
12	8705878.	9673154.	14799925.	24473079.
13	7835255.	9673154.	13155489.	22828643.
14	7051729.	9673154.	11511053.	21184207.
15	6346556.	9673154.	9866617.	19539771.
16	5711901.	9673154.	8222181.	17895335.
17	5140711.	9673154.	6577745.	16250899.
18	4626640.	9673154.	4933309.	14606463.
19	4163976.	9673154.	3288873.	12962026.
20	3747578.	9673154.	1644437.	11317590.

TOTAL

INITIAL INVESTMENT = $ 277423320.
SALVAGE VALUE = $ 0.
INTEREST (%) = 18.
LIFETIME (YEARS) = 20.
CAPITAL RECOVERY FACTOR = .18682
EQUIVALENT ANNUAL COST = $ 51828219.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	27742332.	13871166.	49936198.	77678530.
2	24968099.	13141105.	44942578.	69910677.
3	22471289.	12484049.	40448320.	62919609.
4	20224160.	11896565.	36403488.	56627649.
5	18201744.	11376090.	32763140.	50964884.
6	16381570.	10921047.	29486826.	45868396.
7	14743413.	10531009.	26538143.	41281556.
8	13269072.	10206978.	23884329.	37153401.
9	11942165.	9951804.	21495897.	33438061.
10	10747948.	9770862.	19346307.	30094255.
11	9673154.	9673154.	17411676.	27084830.
12	8705838.	9673154.	15670509.	25343663.
13	7835255.	9673154.	13929341.	23602495.
14	7051729.	9673154.	12188174.	21861328.
15	6346556.	9673154.	10447006.	20120160.
16	5711901.	9673154.	8705839.	18378992.
17	5140711.	9673154.	6964671.	16637825.
18	4626640.	9673154.	5223504.	14896657.
19	4163976.	9673154.	3482336.	13155490.
20	3747578.	9673154.	1741168.	11414322.

TOTAL

```
INITIAL INVESTMENT        = $  277423325.
SALVAGE VALUE             = $          0.
INTEREST (%)              =           19.
LIFETIME (YEARS)          =           20.
CAPITAL RECOVERY FACTOR   =       .19605
EQUIVALENT ANNUAL COST    = $   54387535.
```

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	27742332.	13871166.	52710431.	80452763.
2	24968099.	13141105.	47439388.	72407487.
3	22471289.	12484050.	42695449.	65166738.
4	20224160.	11896565.	38425905.	58650065.
5	18201744.	11376090.	34583314.	52785059.
6	16381570.	10921047.	31124983.	47506553.
7	14743413.	10531009.	28012485.	42755898.
8	13269072.	10206978.	25211236.	38480308.
9	11942165.	9951804.	22690113.	34632277.
10	10747949.	9770862.	20421102.	31169050.
11	9673154.	9673154.	18378992.	28052145.
12	8705838.	9673154.	16541093.	26214246.
13	7835255.	9673154.	14703194.	24376347.
14	7051729.	9673154.	12865295.	22538448.
15	6346556.	9673154.	11027396.	20700549.
16	5711901.	9673154.	9189496.	18862650.
17	5140711.	9673154.	7351597.	17024751.
18	4626640.	9673154.	5513698.	15186852.
19	4163976.	9673154.	3675799.	13348953.
20	3747578.	9673154.	1837900.	11511053.

TOTAL

```
INITIAL INVESTMENT          = $  277423325.
SALVAGE VALUE               = $          0.
INTEREST (%)                =           20.
LIFETIME (YEARS)            =           20.
CAPITAL RECOVERY FACTOR     =       .20536
EQUIVALENT ANNUAL COST      = $   56972696.
```

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	27742532.	13871166.	55484664.	83226996.
2	24968099.	13141165.	49936198.	74904297.
3	22471289.	12404056.	44942578.	67413867.
4	20224160.	11890565.	40448321.	60672481.
5	18201744.	11370090.	36403459.	54605233.
6	16381570.	10921047.	32763140.	49144710.
7	14743413.	10371901.	29486826.	44230239.
8	13269072.	10270978.	26538144.	39807215.
9	11942165.	9951804.	23884329.	35826494.
10	10747948.	9773862.	21495897.	32243845.
11	9673154.	9673154.	19346307.	29019461.
12	8705838.	9673154.	17411676.	27084830.
13	7835255.	9673154.	15477046.	25150200.
14	7051729.	9673154.	13542415.	23215569.
15	6346556.	9673154.	11607785.	21280938.
16	5711901.	9673154.	9673154.	19346308.
17	5140711.	9673154.	7738524.	17411677.
18	4626640.	9673154.	5803893.	15477047.
19	4163976.	9673154.	3869262.	13542416.
20	3747578.	9673154.	1934631.	11607785.

TOTAL

INITIAL INVESTMENT	= $	277427525.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	21.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.21474
EQUIVALENT ANNUAL COST	= $	59575267.

YEAR	DEPRECIATION ($) DOUBLE DECLINING BALANCE	STRAIGHT LINE	CAPITAL ($) RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	27742532.	13871166.	58258697.	86001229.
2	24968299.	13141165.	52433008.	77401107.
3	22471269.	12484056.	47159707.	69660996.
4	20224160.	11825568.	42479737.	62694897.
5	18201744.	11170090.	38223663.	56425407.
6	16381570.	10921047.	34401297.	50782867.
7	14743413.	10531009.	30961167.	45704580.
8	13268074.	10206977.	27865051.	41134122.
9	11942165.	9951804.	25078546.	37020710.
10	10747948.	9771062.	22570691.	33318640.
11	9673154.	9673154.	20313622.	29986776.
12	8705838.	9673154.	18282260.	27955414.
13	7835255.	9673154.	16250898.	25924052.
14	7051729.	9673154.	14219536.	23892690.
15	6346556.	9673154.	12188174.	21861329.
16	5711901.	9673154.	10156812.	19829965.
17	5140711.	9673154.	8125450.	17798603.
18	4626640.	9673154.	6094087.	15767241.
19	4163976.	9673154.	4062725.	13735879.
20	3747578.	9673154.	2031363.	11704517.

TOTAL

INITIAL INVESTMENT	= $	[illegible].
SALVAGE VALUE	= $	.
INTEREST (%)	=	[illegible].
LIFETIME (YEARS)	=	[illegible].
CAPITAL RECOVERY FACTOR	=	.[illegible]
EQUIVALENT ANNUAL COST	= $	[illegible].

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	[illegible]	[illegible]	61033136.	88775462.
2	[illegible]	131411[illegible]	54929817.	79697916.
3	22471289.	124[illegible]	49436836.	71998125.
4	[illegible]	118[illegible]	44492153.	64717313.
5	[illegible]	1137[illegible]	40043837.	59245582.
6	[illegible]	10921047.	36039454.	52421024.
7	14747413.	[illegible]	32435599.	47178921.
8	[illegible]	[illegible]	29191958.	42461029.
9	11943165.	[illegible]	26272762.	38214927.
10	[illegible]	[illegible]	23645490.	34393434.
11	9673154.	9673154.	21260938.	30954091.
12	8705636.	9673154.	19132844.	28823998.
13	[illegible]	9673154.	17024750.	26697964.
14	7051729.	9673154.	14896657.	24569811.
15	6344556.	9673154.	12768565.	22441717.
16	[illegible]	9673154.	10640472.	20313623.
17	5140711.	9673154.	8512376.	18185529.
18	[illegible]	9673154.	6384282.	16057436.
19	[illegible]	9673154.	4256188.	13929342.
20	3747576.	9673154.	2128094.	11801248.

TOTAL

INITIAL INVESTMENT	= $	277427325.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	20.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.20372
EQUIVALENT ANNUAL COST	= $	64339300.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	27742532.	13871166.	55807364.	91549696.
2	24968099.	13141105.	57426627.	82394726.
3	22471289.	12414859.	51683965.	74155254.
4	20224160.	11896565.	46515569.	66739729.
5	18201744.	11378095.	41864012.	60065756.
6	16381570.	10921047.	37677611.	54059181.
7	14743413.	10531069.	33909850.	48653203.
8	13269072.	10206978.	30518865.	43787937.
9	11942165.	9951804.	27466979.	39409143.
10	10747948.	9770802.	24720281.	35468229.
11	9673154.	9673154.	22248253.	31921407.
12	8705838.	9673154.	20023428.	29696582.
13	7835255.	9673154.	17798603.	27471757.
14	7051729.	9673154.	15573778.	25246931.
15	6346556.	9673154.	13348953.	23022106.
16	5711901.	9673154.	11124127.	20797281.
17	5140711.	9673154.	8899302.	18572456.
18	4626640.	9673154.	6674477.	16347630.
19	4163976.	9673154.	4449651.	14122805.
20	3747578.	9673154.	2224826.	11897980.

TOTAL

```
INITIAL INVESTMENT        = $   277423325.
SALVAGE VALUE             = $           0.
INTEREST (%)              =            24.
LIFETIME (YEARS)          =            20.
CAPITAL RECOVERY FACTOR   =        .24329
EQUIVALENT ANNUAL COST    = $    67495373.
```

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	27742332.	13871166.	66581597.	94323929.
2	24968099.	13141105.	59923437.	84891536.
3	22471289.	12484050.	53931094.	76402383.
4	20224160.	11896565.	48537985.	68762145.
5	18201744.	11376090.	43684186.	61885931.
6	16381570.	10921047.	39315768.	55697338.
7	14743413.	10531009.	35384191.	50127604.
8	13269072.	10206978.	31845772.	45114844.
9	11942165.	9951804.	28661195.	40603360.
10	10747948.	9770862.	25795076.	36543024.
11	9673154.	9673154.	23215568.	32888722.
12	8705838.	9673154.	20894012.	30567166.
13	7835255.	9673154.	18572455.	28245609.
14	7051729.	9673154.	16250898.	25924052.
15	6346556.	9673154.	13929342.	23602495.
16	5711901.	9673154.	11607785.	21280939.
17	5140711.	9673154.	9286228.	18959382.
18	4626640.	9673154.	6964671.	16637825.
19	4163976.	9673154.	4643114.	14316268.
20	3747578.	9673154.	2321556.	11994711.

TOTAL

INITIAL INVESTMENT	= $	277423325.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	25.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.25292
EQUIVALENT ANNUAL COST	= $	70164774.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	27742332.	13871166.	69355831.	97098163.
2	24968099.	13141105.	62420248.	87388347.
3	22471289.	12484050.	56178223.	78649512.
4	20224160.	11890565.	50560401.	70784562.
5	18201744.	11376090.	45504361.	63706106.
6	16381570.	10921047.	40953925.	57335495.
7	14743413.	10531069.	36858533.	51601946.
8	13269072.	10206978.	33172680.	46441751.
9	11942165.	9951804.	29855412.	41797577.
10	10747943.	9770862.	26869871.	37617819.
11	9673154.	9673154.	24182884.	33856037.
12	8705838.	9673154.	21764596.	31437750.
13	7835255.	9673154.	19346308.	29019461.
14	7051729.	9673154.	16928019.	26601173.
15	6346556.	9673154.	14509731.	24182885.
16	5711901.	9673154.	12091443.	21764596.
17	5140711.	9673154.	9673154.	19346308.
18	4626640.	9673154.	7254866.	16928020.
19	4163976.	9673154.	4836578.	14509731.
20	3747578.	9673154.	2418289.	12091443.

MODULE 1 (STORAGE)

INITIAL INVESTMENT	= $	239620051.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	5.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.08024
EQUIVALENT ANNUAL COST	= $	19227733.

YEAR	DEPRECIATION ($) DOUBLE DECLINING BALANCE	DEPRECIATION ($) STRAIGHT LINE	CAPITAL ($) RETURN ON UNRECOVERED	CAPITAL ($) RECOVERED PLUS RETURN
1	23962005.	11981002.	11981002.	35943007.
2	21565804.	11350423.	10782902.	32348707.
3	19409224.	10784962.	9704612.	29113836.
4	17468301.	10275472.	8734151.	26202452.
5	15721472.	9825920.	7860736.	23582207.
6	14149325.	9432363.	7074662.	21223987.
7	12734392.	9095994.	6367196.	19101588.
8	11460953.	8816118.	5730477.	17191429.
9	10314858.	8595715.	5157429.	15472287.
10	9283372.	8439429.	4641686.	13925058.
11	8355035.	8355035.	4177517.	12532552.
12	7519532.	8355035.	3759766.	12114801.
13	6767578.	8355035.	3342014.	11697049.
14	6090821.	8355035.	2924262.	11279297.
15	5481739.	8355035.	2506510.	10861545.
16	4933565.	8355035.	2088759.	10443794.
17	4440208.	8355035.	1671007.	10026042.
18	3996188.	8355035.	1253255.	9608290.
19	3596569.	8355035.	835503.	9190538.
20	3236912.	8355035.	417752.	8772787.

MODULE 1 (STORAGE)

```
INITIAL INVESTMENT         = $  239620051.
SALVAGE VALUE              = $          0.
INTEREST (%)               =            6.
LIFETIME (YEARS)           =           20.
CAPITAL RECOVERY FACTOR    =       .08718
EQUIVALENT ANNUAL COST     = $   20891169.
```

YEAR	DEPRECIATION ($) DOUBLE DECLINING BALANCE	DEPRECIATION ($) STRAIGHT LINE	CAPITAL ($) RETURN ON UNRECOVERED	CAPITAL ($) RECOVERED PLUS RETURN
1	23962005.	11981002.	14377203.	38339207.
2	21565804.	11350423.	12939483.	34505287.
3	19409224.	10782902.	11645534.	31054758.
4	17468301.	10275472.	10480981.	27949282.
5	15721472.	9825940.	9432683.	25154354.
6	14149325.	9432663.	8489595.	22638919.
7	12734392.	9095994.	7640635.	20375027.
8	11460953.	8816118.	6876572.	18337525.
9	10314858.	8595715.	6188915.	16503772.
10	9283372.	8439429.	5570023.	14853395.
11	8355035.	8355035.	5013021.	13368056.
12	7519532.	8355035.	4511719.	12866754.
13	6767578.	8355035.	4010417.	12365452.
14	6090821.	8355035.	3509115.	11864150.
15	5481739.	8355035.	3007813.	11362847.
16	4933565.	8355035.	2506510.	10861545.
17	4440208.	8355035.	2005208.	10360243.
18	3996188.	8355035.	1503906.	9858941.
19	3596569.	8355035.	1002604.	9357639.
20	3236912.	8355035.	501302.	8856337.

AD-A144 651 EAST COAST REGIONAL PETROLEUM RESERVE (RPR) VOLUME 3 POTENTIAL STORAGE SI..(U) ARMY ENGINEER DIV HUNTSVILLE AL R E SHANNON ET AL. 30 SEP 80 HNDTR-80-45-SP-VOL-3 4/4

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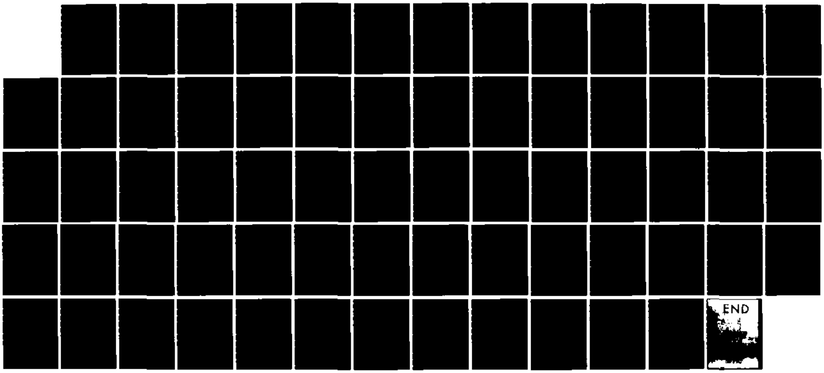

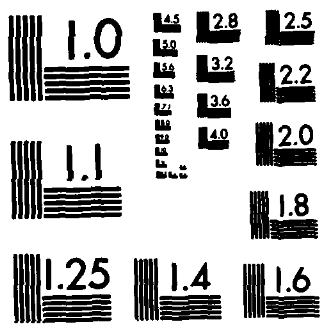

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

MODULE 1 (STORAGE)

INITIAL INVESTMENT	= $	239620051.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	7.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.09439
EQUIVALENT ANNUAL COST	= $	22618438.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	23962005.	11981002.	16773403.	40735408.
2	21565804.	11350423.	15096063.	36661867.
3	19409224.	10782902.	13586457.	32995681.
4	17468301.	10275472.	12227811.	29696112.
5	15721472.	9825920.	11005030.	26726502.
6	14149325.	9432883.	9904527.	24053852.
7	12734392.	9095994.	8914074.	21648467.
8	11460953.	8816118.	8022667.	19483620.
9	10314858.	8595715.	7220400.	17535258.
10	9283372.	8439429.	6498360.	15781732.
11	8355035.	8355035.	5848524.	14203559.
12	7519532.	8355035.	5263672.	13618707.
13	6767578.	8355035.	4678819.	13033854.
14	6090821.	8355035.	4093967.	12449002.
15	5481739.	8355035.	3509115.	11864150.
16	4933565.	8355035.	2924262.	11279297.
17	4440208.	8355035.	2339410.	10694445.
18	3996188.	8355035.	1754557.	10109592.
19	3596569.	8355035.	1169705.	9524740.
20	3236912.	8355035.	584852.	8939887.

MODULE 1 (STORAGE)

INITIAL INVESTMENT	= $	239620051.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	8.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.10185
EQUIVALENT ANNUAL COST	= $	24405631.

YEAR	DEPRECIATION ($) DOUBLE DECLINING BALANCE	DEPRECIATION ($) STRAIGHT LINE	CAPITAL ($) RETURN ON UNRECOVERED	CAPITAL ($) RECOVERED PLUS RETURN
1	23962005.	11981002.	19169604.	43131608.
2	21565804.	11350423.	17252643.	38618447.
3	19409224.	10782902.	15527379.	34936603.
4	17468301.	10275472.	13974641.	31442943.
5	15721472.	9825920.	12577177.	28298649.
6	14149325.	9432863.	11319460.	25468784.
7	12734392.	9095994.	10187514.	22921906.
8	11460953.	8516113.	9168762.	20629715.
9	10314858.	8595715.	8251886.	18566744.
10	9283372.	8479429.	7426698.	16710079.
11	8355035.	8355035.	6684028.	15039063.
12	7519532.	8355035.	6015625.	14370660.
13	6767578.	8355035.	5347222.	13702257.
14	6090821.	8355035.	4678819.	13073854.
15	5481739.	8355035.	4010417.	12365452.
16	4933565.	8355035.	3342014.	11697049.
17	4440206.	8355035.	2673611.	11028646.
18	3996186.	8355035.	2005208.	10360243.
19	3596569.	8355035.	1336806.	9691840.
20	3236912.	8355035.	668403.	9023438.

MODULE 1 (STORAGE)

INITIAL INVESTMENT	= $	23962051.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	9.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.10955
EQUIVALENT ANNUAL COST	= $	26249532.

YEAR	DEPRECIATION ($) DOUBLE DECLINING BALANCE	STRAIGHT LINE	CAPITAL ($) RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	23962005.	11981002.	21565804.	45527809.
2	21565804.	11350423.	19409224.	40975028.
3	19409224.	10782962.	17468302.	36877525.
4	17468301.	10275472.	15721471.	33189773.
5	15721472.	9825920.	14149324.	29870796.
6	14149325.	9432863.	12734392.	26883717.
7	12734392.	9095994.	11460953.	24195345.
8	11460953.	8816115.	10314858.	21775811.
9	10314858.	8595715.	9283372.	19598230.
10	9283372.	8439429.	8355035.	17638407.
11	8355035.	8355035.	7519531.	15874566.
12	7519532.	8355035.	6767578.	15122613.
13	6767578.	8355035.	6015625.	14370660.
14	6090821.	8355035.	5263672.	13618707.
15	5481739.	8355035.	4511719.	12866754.
16	4933565.	8355035.	3759766.	12114801.
17	4440208.	8355035.	3007813.	11362847.
18	3996188.	8355035.	2255859.	10610894.
19	3596569.	8355035.	1503906.	9858941.
20	3236912.	8355035.	751953.	9106988.

MODULE 1 (STORAGE)

INITIAL INVESTMENT	= $	239620051.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	10.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.11746
EQUIVALENT ANNUAL COST	= $	28145681.

YEAR	DEPRECIATION ($) DOUBLE DECLINING BALANCE	STRAIGHT LINE	CAPITAL ($) RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	23962005.	11981002.	23962005.	47924009.
2	21565804.	11350423.	21565804.	43131609.
3	19409224.	10782962.	19409224.	38818448.
4	17468301.	10275472.	17468301.	34936603.
5	15721472.	9825920.	15721472.	31442943.
6	14149325.	9432863.	14149325.	28298649.
7	12734392.	9095994.	12734392.	25468784.
8	11460953.	8816118.	11460953.	22921906.
9	10314858.	8595715.	10314858.	20629715.
10	9283372.	8439429.	9283372.	18566744.
11	8355035.	8355035.	8355035.	16710070.
12	7519532.	8355035.	7519531.	15874566.
13	6767578.	8355035.	6684028.	15039063.
14	6090821.	8355035.	5848524.	14203559.
15	5481739.	8355035.	5013021.	13368056.
16	4933565.	8355035.	4177517.	12532552.
17	4440208.	8355035.	3342014.	11697049.
18	3996188.	8355035.	2506510.	10861545.
19	3596569.	8355035.	1671007.	10026042.
20	3236912.	8355035.	835503.	9190538.

MODULE 1 (STORAGE)

INITIAL INVESTMENT = $ 239620051.
SALVAGE VALUE = $ 0.
INTEREST (%) = 11.
LIFETIME (YEARS) = 20.
CAPITAL RECOVERY FACTOR = .12558
EQUIVALENT ANNUAL COST = $ 30090440.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	23962005.	11981002.	26358205.	50320210.
2	21565804.	11350423.	23722385.	45288169.
3	19409224.	10782902.	21350146.	40759370.
4	17468301.	10273472.	19215132.	36683433.
5	15721472.	9825920.	17293619.	33015090.
6	14149325.	9432863.	15564257.	29713582.
7	12734392.	9095994.	14007831.	26742224.
8	11460953.	8816118.	12607048.	24068001.
9	10314858.	8595715.	11346344.	21661201.
10	9283372.	8439429.	10211709.	19495081.
11	8355035.	8355035.	9190538.	17545573.
12	7519532.	8355035.	8271485.	16626519.
13	6767578.	8355035.	7352431.	15707466.
14	6090821.	8355035.	6433377.	14788412.
15	5481739.	8355035.	5514323.	13869358.
16	4933565.	8355035.	4595269.	12950304.
17	4440208.	8355035.	3676215.	12031250.
18	3996188.	8355035.	2757162.	11112196.
19	3596569.	8355035.	1838108.	10193143.
20	3236912.	8355035.	919054.	9274089.

MODULE 1 (STORAGE)

INITIAL INVESTMENT	= $	239620051.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	12.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.13388
EQUIVALENT ANNUAL COST	= $	32080040.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	23962005.	11981002.	28754406.	52716410.
2	21565804.	11350423.	25878965.	47444769.
3	19409224.	10782902.	23291069.	42700292.
4	17468301.	10275472.	20961962.	38430263.
5	15721472.	9825920.	18865766.	34587237.
6	14149325.	9432883.	16979189.	31128514.
7	12734392.	9095994.	15281271.	28015663.
8	11460953.	8816118.	13753144.	25214097.
9	10314858.	8595715.	12377829.	22692687.
10	9283372.	8439429.	11140046.	20423418.
11	8355035.	8355035.	10026042.	18381077.
12	7519532.	8355035.	9023438.	17378472.
13	6767578.	8355035.	8020833.	16375868.
14	6090821.	8355035.	7018229.	15373264.
15	5481739.	8355035.	6015625.	14370660.
16	4933565.	8355035.	5013021.	13368056.
17	4440208.	8355035.	4010417.	12365452.
18	3996188.	8355035.	3007813.	11362847.
19	3596569.	8355035.	2005208.	10360243.
20	3236912.	8355035.	1002604.	9357639.

MODULE 1 (STORAGE)

INITIAL INVESTMENT	= $	239620051.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	13.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.14235
EQUIVALENT ANNUAL COST	= $	34110621.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	23962005.	11981002.	31150606.	55112611.
2	21565804.	11350420.	28035546.	49601350.
3	19409224.	10782902.	25231991.	44641215.
4	17468301.	10270472.	22708792.	40177093.
5	15721472.	9823927.	20437913.	36159384.
6	14149325.	9432883.	18394122.	32543446.
7	12734392.	9095994.	16554710.	29289102.
8	11460953.	8816118.	14899239.	26360192.
9	10314858.	8595715.	13409315.	23724173.
10	9283372.	8479429.	12068384.	21351756.
11	8355035.	8355035.	10861545.	19216580.
12	7519532.	8355035.	9775391.	18130426.
13	6767578.	8355035.	8609236.	17044271.
14	6090821.	8355035.	7603082.	15958117.
15	5481739.	8355035.	6516927.	14871962.
16	4933565.	8355035.	5430773.	13785808.
17	4440208.	8355035.	4344618.	12699653.
18	3996188.	8355035.	3258464.	11613498.
19	3596569.	8355035.	2172309.	10527344.
20	3236912.	8355035.	1086155.	9441189.

MODULE 1 (STORAGE)

```
INITIAL INVESTMENT         = $  239620051.
SALVAGE VALUE              = $          0.
INTEREST (%)               =           14.
LIFETIME (YEARS)           =           20.
CAPITAL RECOVERY FACTOR    =       .15099
EQUIVALENT ANNUAL COST     = $   36179273.
```

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	23962005.	11981002.	33546806.	57508811.
2	21565804.	11350423.	30192126.	51757930.
3	19409224.	10782902.	27172913.	46582137.
4	17468301.	10275472.	24455622.	41923923.
5	15721472.	9825920.	22010060.	37731531.
6	14149325.	9432853.	19809054.	33958379.
7	12734392.	9095994.	17828149.	30562541.
8	11460953.	8816118.	16045334.	27506287.
9	10314858.	8595715.	14440801.	24755658.
10	9283372.	8439429.	12996721.	22280093.
11	8355035.	8355035.	11697049.	20052084.
12	7519532.	8355035.	10527344.	18882379.
13	6767578.	8355035.	9357639.	17712674.
14	6090821.	8355035.	8187934.	16542969.
15	5481739.	8355035.	7018229.	15373264.
16	4933565.	8355035.	5848524.	14203559.
17	4440208.	8355035.	4678819.	13033854.
18	3996188.	8355035.	3509115.	11864150.
19	3596569.	8355035.	2339410.	10694445.
20	3236912.	8355035.	1169705.	9524740.

MODULE 1 (STORAGE)

INITIAL INVESTMENT	= $	239620051.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	15.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.15976
EQUIVALENT ANNUAL COST	= $	38282050.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	23962005.	11981062.	35943007.	59905011.
2	21565604.	11350423.	32348706.	53914511.
3	19409224.	10782902.	29113836.	48523060.
4	17468301.	10275472.	26202452.	43670753.
5	15721472.	9625920.	23582207.	39303678.
6	14149325.	9432863.	21223987.	35373311.
7	12734392.	9095994.	19101586.	31835980.
8	11460953.	8616118.	17191429.	28652382.
9	10314858.	8595715.	15472287.	25787144.
10	9283372.	8439469.	13925058.	23206430.
11	8355035.	8355035.	12532552.	20887587.
12	7519532.	8355035.	11279297.	19634332.
13	6767578.	8355035.	10026042.	18381077.
14	6090821.	8355035.	8772787.	17127821.
15	5461739.	8355035.	7519531.	15674566.
16	4933565.	8355035.	6266276.	14621311.
17	4440208.	8355035.	5013021.	13368056.
18	3996198.	8355035.	3759766.	12114801.
19	3596569.	8355035.	2506510.	10861545.
20	3236912.	8355035.	1253255.	9608290.

MODULE 1 (STORAGE)

INITIAL INVESTMENT	= $	239620051.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	16.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.16867
EQUIVALENT ANNUAL COST	= $	40416002.

YEAR	DEPRECIATION ($) DOUBLE DECLINING BALANCE	DEPRECIATION ($) STRAIGHT LINE	CAPITAL ($) RETURN ON UNRECOVERED	CAPITAL ($) RECOVERED PLUS RETURN
1	23962095.	11921002.	36339207.	62301212.
2	21565894.	11350423.	34505286.	56071091.
3	19409224.	10782952.	31054758.	50463962.
4	17468301.	10275473.	27949282.	45417584.
5	15721472.	9825920.	25154354.	40875826.
6	14149325.	9432963.	22638919.	36768243.
7	12734392.	9095994.	20375027.	33109420.
8	11460955.	8816118.	18337525.	29798478.
9	10314858.	8595715.	16503772.	26818630.
10	9283372.	8439429.	14853395.	24136767.
11	8355035.	8355035.	13368056.	21723091.
12	7519532.	8355035.	12031250.	20386285.
13	6767576.	8355035.	10694445.	19049479.
14	6090821.	8355035.	9357639.	17712674.
15	5481739.	8355035.	8020833.	16375868.
16	4933565.	8355035.	6684028.	15039063.
17	4440206.	8355035.	5347222.	13702257.
18	3996186.	8355035.	4010417.	12365452.
19	3596569.	8355035.	2673611.	11028646.
20	3236912.	8355035.	1336806.	9691840.

MODULE 1 (STORAGE)

INITIAL INVESTMENT = $ 239620051.
SALVAGE VALUE = $ 0.
INTEREST (%) = 17.
LIFETIME (YEARS) = 20.
CAPITAL RECOVERY FACTOR = .17769
EQUIVALENT ANNUAL COST = $ 42578172.

YEAR	DEPRECIATION ($) DOUBLE DECLINING BALANCE	DEPRECIATION ($) STRAIGHT LINE	CAPITAL ($) RETURN ON UNRECOVERED	CAPITAL ($) RECOVERED PLUS RETURN
1	23962005.	11981002.	40735406.	64697412.
2	21565804.	11350423.	36661867.	58227672.
3	19409224.	10782902.	32995681.	52404905.
4	17468301.	10275472.	29696113.	47164414.
5	15721472.	9825920.	26726502.	42447973.
6	14149325.	9432883.	24053852.	38203176.
7	12734392.	9095994.	21648467.	34382859.
8	11460953.	8816118.	19483620.	30944573.
9	10314858.	8595715.	17535258.	27850116.
10	9283372.	8439429.	15781733.	25065105.
11	8355035.	8355035.	14203559.	22558594.
12	7519532.	8355035.	12783203.	21138238.
13	6767578.	8355035.	11362847.	19717882.
14	6090821.	8355035.	9942492.	18297526.
15	5481739.	8355035.	8522136.	16877170.
16	4933565.	8355035.	7101780.	15456815.
17	4440208.	8355035.	5681424.	14036459.
18	3996188.	8355035.	4261068.	12616103.
19	3596569.	8355035.	2840712.	11195747.
20	3236912.	8355035.	1420356.	9775391.

MODULE 1 (STORAGE)

INITIAL INVESTMENT	= $	239620051.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	18.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.18682
EQUIVALENT ANNUAL COST	= $	44765812.

YEAR	DEPRECIATION ($) DOUBLE DECLINING BALANCE	DEPRECIATION ($) STRAIGHT LINE	CAPITAL ($) RETURN ON UNRECOVERED	CAPITAL ($) RECOVERED PLUS RETURN
1	23962005.	11981002.	43131608.	67093613.
2	21565804.	11351423.	38818448.	60384252.
3	19409224.	10732902.	34936603.	54345827.
4	17468301.	10275472.	31442943.	48911244.
5	15721472.	9825920.	28298649.	44020120.
6	14149325.	9432863.	25468784.	39618109.
7	12734392.	9095994.	22921906.	35656298.
8	11460953.	8816119.	20629715.	32090668.
9	10314858.	8595715.	18566744.	28881602.
10	9283372.	8439429.	16710070.	25993442.
11	8355075.	8355035.	15039063.	23394098.
12	7519532.	8355035.	13535157.	21890191.
13	6767576.	8355035.	12031250.	20386285.
14	6090821.	8355035.	10527344.	18882379.
15	5481739.	8355035.	9023438.	17378473.
16	4933565.	8355035.	7519531.	15874566.
17	4440208.	8355035.	6015625.	14370660.
18	3996188.	8355035.	4511719.	12866754.
19	3596569.	8355035.	3007813.	11362847.
20	3236912.	8355035.	1503906.	9858941.

MODULE 1 (STORAGE)

INITIAL INVESTMENT	= $	239620051.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	19.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.19605
EQUIVALENT ANNUAL COST	= $	46975381.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	23962005.	11981002.	45527809.	69439813.
2	21565804.	11350423.	40975028.	62540833.
3	19409224.	10782902.	36877525.	56286749.
4	17468301.	10275472.	33189773.	50656074.
5	15721472.	9825920.	29870796.	45592267.
6	14149325.	9432863.	26383717.	41033041.
7	12734392.	9095974.	24195345.	36929737.
8	11460953.	8816118.	21775811.	33236764.
9	10314858.	8595715.	19598230.	29913087.
10	9283372.	8439429.	17638407.	26921779.
11	8355035.	8355035.	15874566.	24229601.
12	7519532.	8355035.	14287110.	22642145.
13	6767578.	8355035.	12699653.	21054688.
14	6090821.	8355035.	11112196.	19467231.
15	5481739.	8355035.	9524740.	17879775.
16	4933565.	8355035.	7937283.	16292318.
17	4440208.	8355035.	6349827.	14704861.
18	3996188.	8355035.	4762370.	13117405.
19	3596569.	8355035.	3174913.	11529948.
20	3236912.	8355035.	1587457.	9942492.

MODULE 1 (STORAGE)

```
INITIAL INVESTMENT         = $  239620051.
SALVAGE VALUE              = $          0.
INTEREST (%)               =           20.
LIFETIME (YEARS)           =           20.
CAPITAL RECOVERY FACTOR    =       .20536
EQUIVALENT ANNUAL COST     = $   49207541.
```

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	23962005.	11981002.	47924009.	71886014.
2	21565804.	11350423.	43131609.	64697413.
3	19409224.	10782902.	38818448.	58227672.
4	17468301.	10275472.	34936603.	52404904.
5	15721472.	9825920.	31442943.	47164414.
6	14149325.	9432883.	28298649.	42447973.
7	12734392.	9095994.	25468784.	38203176.
8	11460953.	8816119.	22921906.	34382859.
9	10314858.	8595715.	20629715.	30944573.
10	9283372.	8479429.	18566744.	27850116.
11	8355035.	8355035.	16710070.	25065105.
12	7519532.	8355035.	15039063.	23394098.
13	6767578.	8355035.	13368056.	21723091.
14	6090821.	8355035.	11697049.	20052084.
15	5481739.	8355035.	10026042.	18381077.
16	4933565.	8355035.	8355035.	16710070.
17	4440208.	8355035.	6684028.	15039063.
18	3996188.	8355035.	5013021.	13368056.
19	3596569.	8355035.	3342014.	11697049.
20	3236912.	8355035.	1671007.	10026042.

MODULE 1 (STORAGE)

INITIAL INVESTMENT	= $	239620051.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	21.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.21474
EQUIVALENT ANNUAL COST	= $	51457152.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	23962005.	11981002.	50320210.	74282214.
2	21565804.	11350423.	45288189.	66853993.
3	19409224.	10782902.	40759370.	60168594.
4	17468301.	10275472.	36683433.	54151735.
5	15721472.	9825940.	33015090.	48736562.
6	14149325.	9432363.	29713582.	43862906.
7	12734392.	9095994.	26742224.	39476616.
8	11460953.	8816118.	24068001.	35528954.
9	10314858.	8595715.	21661201.	31976059.
10	9283372.	8439469.	19495081.	28778453.
11	8355035.	8355035.	17545573.	25900608.
12	7519532.	8355035.	15791016.	24146051.
13	6767578.	8355035.	14034459.	22391493.
14	6090821.	8355035.	12281901.	20636936.
15	5481739.	8355035.	10527344.	18882379.
16	4933565.	8355035.	8772787.	17127821.
17	4440208.	8355035.	7018229.	15373264.
18	3996188.	8355035.	5263672.	13618707.
19	3596569.	8355035.	3509115.	11864150.
20	3236912.	8355035.	1754557.	10109592.

MODULE 1 (STORAGE)

```
INITIAL INVESTMENT        = $   239620051.
SALVAGE VALUE             = $           0.
INTEREST (%)              =            22.
LIFETIME (YEARS)          =            20.
CAPITAL RECOVERY FACTOR   =        .22420
EQUIVALENT ANNUAL COST    = $    53723262.
```

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	23962005.	11981002.	52716410.	76678415.
2	21565804.	11350423.	47444769.	69010574.
3	19409224.	10782902.	42700293.	62109517.
4	17468301.	10275472.	38430263.	55898565.
5	15721472.	9825920.	34587237.	50308709.
6	14149325.	9432883.	31128514.	45277838.
7	12734392.	9095994.	28015663.	40750055.
8	11460953.	8816118.	25214097.	36675049.
9	10314658.	8595715.	22692637.	33007545.
10	9283372.	8439429.	20423416.	29706790.
11	8355035.	8355035.	18381077.	26736112.
12	7319532.	8355035.	16542969.	24898004.
13	6767578.	8355035.	14704861.	23059896.
14	6090821.	8355035.	12866754.	21221789.
15	5481739.	8355035.	11028646.	19383681.
16	4933565.	8355035.	9190538.	17545573.
17	4440208.	8355035.	7352431.	15707466.
18	3996188.	8355035.	5514323.	13869359.
19	3596569.	8355035.	3676215.	12031250.
20	3236912.	8355035.	1838108.	10193143.

MODULE 1 (STORAGE)

INITIAL INVESTMENT	= $	239620051.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	23.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.23372
EQUIVALENT ANNUAL COST	= $	56004103.

YEAR	DEPRECIATION ($) DOUBLE DECLINING BALANCE	STRAIGHT LINE	CAPITAL ($) RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	23962005.	11981002.	55112611.	79074615.
2	21565804.	11350423.	49601350.	71167154.
3	19409224.	10782902.	44641215.	64050439.
4	17468301.	10275472.	40177093.	57645395.
5	15721472.	9825920.	36159384.	51880856.
6	14149325.	9432883.	32543447.	46692771.
7	12734392.	9095994.	29289102.	42023494.
8	11460953.	8816118.	26360192.	37821145.
9	10314858.	8595715.	23724173.	34039030.
10	9283372.	8439429.	21351756.	30635128.
11	8355035.	8355035.	19216580.	27571615.
12	7519532.	8355035.	17294922.	25649957.
13	6767578.	8355035.	15373264.	23728299.
14	6090821.	8355035.	13451606.	21806641.
15	5481739.	8355035.	11529948.	19884983.
16	4933565.	8355035.	9608290.	17963325.
17	4440208.	8355035.	7686632.	16041667.
18	3996188.	8355035.	5764974.	14120009.
19	3596569.	8355035.	3843316.	12198351.
20	3236912.	8355035.	1921658.	10276693.

MODULE 1 (STORAGE)

INITIAL INVESTMENT = \$ 239620051.
SALVAGE VALUE = \$ 0.
INTEREST (%) = 24.
LIFETIME (YEARS) = 20.
CAPITAL RECOVERY FACTOR = .24329
EQUIVALENT ANNUAL COST = \$ 58295071.

	DEPRECIATION (\$)		CAPITAL (\$)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	23962005.	11981002.	57508811.	81470816.
2	21565804.	11350423.	51757930.	73323735.
3	19409224.	10782903.	46582137.	65991361.
4	17468301.	10275472.	41923924.	59392225.
5	15721472.	9525940.	37731532.	53453003.
6	14149325.	9432883.	33958379.	48107703.
7	12734392.	9093994.	30562541.	43296933.
8	11460953.	8816118.	27506287.	38967240.
9	10314858.	8595713.	24755659.	35070516.
10	9283372.	8479409.	22280093.	31563465.
11	8355035.	8355035.	20052084.	28407119.
12	7519532.	8355035.	18046875.	26401910.
13	6767578.	8355035.	16041667.	24396702.
14	6090821.	8355035.	14036459.	22391494.
15	5481739.	8355035.	12031250.	20386285.
16	4933565.	8355035.	10026042.	18381077.
17	4440208.	8355035.	8020833.	16375868.
18	3996187.	8355035.	6015625.	14370660.
19	3596569.	8355035.	4010417.	12365452.
20	3236912.	8355035.	2005208.	10360243.

MODULE 1 (STORAGE)

INITIAL INVESTMENT	= $	239620051.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	25.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.25292
EQUIVALENT ANNUAL COST	= $	60603725.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	23962005.	11981002.	59905012.	83867017.
2	21565804.	11350423.	53914511.	75480316.
3	19409224.	10782902.	48523060.	67932284.
4	17468301.	10275472.	43670754.	61139056.
5	15721472.	9825920.	39303679.	55025151.
6	14149325.	9432883.	35373312.	49522636.
7	12734392.	9095994.	31835981.	44570373.
8	11460953.	8816118.	28652383.	40113336.
9	10314858.	8595715.	25787145.	36102002.
10	9283372.	8439429.	23208430.	32491802.
11	8355035.	8355035.	20887587.	29242622.
12	7519532.	8355035.	18798829.	27153864.
13	6767576.	8355035.	16710070.	25065105.
14	6090821.	8355035.	14621311.	22976346.
15	5481739.	8355035.	12532552.	20887587.
16	4933565.	8355035.	10443794.	18798829.
17	4440208.	8355035.	8355035.	16710070.
18	3996188.	8355035.	6266276.	14621311.
19	3596569.	8355035.	4177517.	12532552.
20	3236912.	8355035.	2088759.	10443794.

MODULE 3 (DOCK/TERM)

INITIAL INVESTMENT	= $	31892187.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	5.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.08024
EQUIVALENT ANNUAL COST	= $	2559112.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	3189219.	1594609.	1594609.	4783828.
2	2870297.	1510683.	1435146.	4305445.
3	2583267.	1435143.	1291634.	3874901.
4	2324940.	1367612.	1162470.	3487411.
5	2092446.	1307779.	1046223.	3138670.
6	1883202.	1255408.	941601.	2824803.
7	1694882.	1210830.	847441.	2542722.
8	1525393.	1175386.	762697.	2288090.
9	1372854.	1144045.	686427.	2059281.
10	1235569.	1123244.	617784.	1853353.
11	1112012.	1112012.	556006.	1668018.
12	1000811.	1112012.	500405.	1612417.
13	900730.	1112012.	444805.	1556817.
14	810657.	1112012.	389204.	1501216.
15	729591.	1112012.	333604.	1445615.
16	656632.	1112012.	278003.	1390015.
17	590969.	1112012.	222402.	1334414.
18	531872.	1112012.	166802.	1278814.
19	478685.	1112012.	111201.	1223213.
20	430816.	1112012.	55601.	1167612.

MODULE 2 (DOCK/TERM)

INITIAL INVESTMENT	= $	31892187.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	6.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.08718
EQUIVALENT ANNUAL COST	= $	2780506.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	3189219.	1594609.	1913531.	5102750.
2	2870297.	1510683.	1722178.	4592475.
3	2583267.	1435148.	1549960.	4133227.
4	2324940.	1367612.	1394964.	3719905.
5	2092446.	1307779.	1255468.	3347914.
6	1883202.	1255468.	1129921.	3013123.
7	1694882.	1210630.	1016929.	2711811.
8	1525393.	1173360.	915236.	2440630.
9	1372854.	1144045.	823712.	2196567.
10	1235569.	1123244.	741341.	1976910.
11	1112012.	1112012.	667207.	1779219.
12	1000811.	1112012.	600486.	1712498.
13	900730.	1112012.	533766.	1645778.
14	810657.	1112012.	467045.	1579057.
15	729591.	1112012.	400324.	1512336.
16	656632.	1112012.	333604.	1445615.
17	590969.	1112012.	266883.	1378895.
18	531872.	1112012.	200162.	1312174.
19	478685.	1112012.	133441.	1245453.
20	430816.	1112012.	66721.	1178733.

MODULE 2 (DOCK/TERM)

INITIAL INVESTMENT	= $	31892187.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	7.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.09439
EQUIVALENT ANNUAL COST	= $	3010397.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	3189219.	1594609.	2232453.	5421672.
2	2870297.	1510683.	2009208.	4879505.
3	2583267.	1435148.	1808287.	4391554.
4	2324940.	1367612.	1627458.	3952399.
5	2092446.	1307779.	1464712.	3557159.
6	1883202.	1255468.	1318241.	3201443.
7	1694882.	1210630.	1186417.	2881299.
8	1525393.	1173380.	1067775.	2593169.
9	1372854.	1144045.	960998.	2333852.
10	1235569.	1123244.	864898.	2100467.
11	1112012.	1112012.	778408.	1890420.
12	1000811.	1112012.	700567.	1812579.
13	900730.	1112012.	622727.	1734739.
14	810657.	1112012.	544886.	1656898.
15	729591.	1112012.	467045.	1579057.
16	656632.	1112012.	389204.	1501216.
17	590969.	1112012.	311363.	1423375.
18	531872.	1112012.	233522.	1345534.
19	478685.	1112012.	155682.	1267694.
20	430816.	1112012.	77841.	1189853.

MODULE 2 (DOCK/TERM)

INITIAL INVESTMENT	= $	31892167.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	8.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.10185
EQUIVALENT ANNUAL COST	= $	3249290.

YEAR	DEPRECIATION ($) DOUBLE DECLINING BALANCE	DEPRECIATION ($) STRAIGHT LINE	CAPITAL ($) RETURN ON UNRECOVERED	CAPITAL ($) RECOVERED PLUS RETURN
1	3189219.	1594609.	2551375.	5740594.
2	2870297.	1510683.	2296237.	5166534.
3	2583267.	1435148.	2066614.	4649881.
4	2324940.	1367612.	1859952.	4184893.
5	2092446.	1307779.	1673957.	3766404.
6	1883202.	1255468.	1506561.	3389763.
7	1694882.	1210630.	1355905.	3050787.
8	1525393.	1175360.	1220315.	2745708.
9	1372854.	1144045.	1098283.	2471137.
10	1235569.	1123244.	988455.	2224024.
11	1112012.	1112012.	889609.	2001621.
12	1000811.	1112012.	800649.	1912660.
13	900730.	1112012.	711638.	1823699.
14	810657.	1112012.	622727.	1734739.
15	729591.	1112012.	533766.	1645778.
16	656632.	1112012.	444805.	1556817.
17	590969.	1112012.	355844.	1467856.
18	531872.	1112012.	266883.	1378895.
19	478685.	1112012.	177922.	1289934.
20	430816.	1112012.	88961.	1200973.

MODULE 2 (DOCK/TERM)

INITIAL INVESTMENT	= $	31892137.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	9.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.10955
EQUIVALENT ANNUAL COST	= $	3493677.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	3189219.	1594609.	2870297.	6059515.
2	2870297.	1516683.	2583267.	5453564.
3	2583267.	1435148.	2324940.	4908208.
4	2324940.	1367612.	2092446.	4417387.
5	2092446.	1307779.	1883202.	3975648.
6	1883202.	1255469.	1694882.	3578083.
7	1694882.	1210609.	1525393.	3220275.
8	1525393.	1173380.	1372854.	2898248.
9	1372854.	1144045.	1235569.	2608423.
10	1235569.	1122244.	1112012.	2347581.
11	1112012.	1112012.	1000811.	2112823.
12	1000811.	1112012.	900730.	2012741.
13	900730.	1112012.	800649.	1912660.
14	810657.	1112012.	700567.	1812579.
15	729591.	1112012.	600486.	1712498.
16	656632.	1112012.	500405.	1612417.
17	590969.	1112012.	400324.	1512336.
18	531872.	1112012.	300243.	1412255.
19	478685.	1112012.	200162.	1312174.
20	430816.	1112012.	100081.	1212093.

MODULE 3 (DOCK/TERM)

INITIAL INVESTMENT = $ 31892187.
SALVAGE VALUE = $ 0.
INTEREST (%) = 10.
LIFETIME (YEARS) = 20.
CAPITAL RECOVERY FACTOR = .11746
EQUIVALENT ANNUAL COST = $ 3746044.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	3189219.	1594609.	3189219.	6378437.
2	2870297.	1510683.	2870297.	5740594.
3	2583267.	1430143.	2583267.	5166534.
4	2324940.	1347612.	2324940.	4649881.
5	2092446.	1307779.	2092446.	4184893.
6	1883202.	1255408.	1883202.	3766404.
7	1694882.	1210655.	1694882.	3389763.
8	1525393.	1175360.	1525393.	3050787.
9	1372854.	1144045.	1372854.	2745708.
10	1235569.	1123244.	1235569.	2471137.
11	1112012.	1112012.	1112012.	2224024.
12	1000811.	1112012.	1000811.	2112823.
13	900730.	1112012.	889610.	2001621.
14	810657.	1112012.	778408.	1890420.
15	729591.	1112012.	667207.	1779219.
16	656632.	1112012.	556006.	1668018.
17	590969.	1112012.	444805.	1556817.
18	531872.	1112012.	333604.	1445615.
19	478685.	1112012.	222402.	1334414.
20	430816.	1112012.	111201.	1223213.

MODULE 2 (DOCK/TERM)

INITIAL INVESTMENT	= $	31892197.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	11.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.12558
EQUIVALENT ANNUAL COST	= $	4004852.

YEAR	DEPRECIATION ($) DOUBLE DECLINING BALANCE	STRAIGHT LINE	CAPITAL ($) RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	3189219.	1594609.	3508141.	6697359.
2	2870297.	1510683.	3157326.	6027623.
3	2583267.	1435149.	2841594.	5424861.
4	2324940.	1367612.	2557434.	4882375.
5	2092446.	1307779.	2301691.	4394137.
6	1883202.	1255468.	2071522.	3954724.
7	1694882.	1210630.	1864370.	3559251.
8	1525393.	1173380.	1677933.	3203326.
9	1372854.	1144045.	1510140.	2882994.
10	1235569.	1123244.	1359126.	2594694.
11	1112012.	1112012.	1223213.	2335225.
12	1000811.	1112012.	1100892.	2212904.
13	900730.	1112012.	978570.	2090582.
14	810657.	1112012.	856249.	1968261.
15	729591.	1112012.	733928.	1845940.
16	656632.	1112012.	611607.	1723618.
17	590969.	1112012.	489285.	1601297.
18	531872.	1112012.	366964.	1478976.
19	478685.	1112012.	244643.	1356654.
20	430816.	1112012.	122321.	1234333.

MODULE 2 (LOCK/TERM)

```
INITIAL INVESTMENT          = $   31892167.
SALVAGE VALUE               = $          0.
INTEREST (%)                =           12.
LIFETIME (YEARS)            =           20.
CAPITAL RECOVERY FACTOR     =       .13388
EQUIVALENT ANNUAL COST      = $    4269687.
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	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	3189219.	1594609.	3827062.	7016281.
2	2870297.	1510681.	3444356.	6314653.
3	2583267.	1435147.	3099921.	5683188.
4	2324940.	1367612.	2789929.	5114869.
5	2092446.	1307779.	2510936.	4603382.
6	1883202.	1255468.	2259842.	4143044.
7	1694882.	1210630.	2031858.	3726740.
8	1525393.	1173380.	1830472.	3355866.
9	1372854.	1144045.	1647425.	3020279.
10	1235569.	1123244.	1482682.	2718251.
11	1112012.	1112012.	1334414.	2446426.
12	1000811.	1112012.	1200973.	2312985.
13	900730.	1112012.	1067531.	2179543.
14	810657.	1112012.	934090.	2046102.
15	729591.	1112012.	800649.	1912660.
16	656632.	1112012.	667207.	1779219.
17	590969.	1112012.	533766.	1645778.
18	531872.	1112012.	400324.	1512336.
19	478685.	1112012.	266883.	1378895.
20	430816.	1112012.	133441.	1245453.

MODULE 2 (DOCK/TERM)

INITIAL INVESTMENT	= $	31892187.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	13.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.14235
EQUIVALENT ANNUAL COST	= $	4539974.

YEAR	DEPRECIATION ($) DOUBLE DECLINING BALANCE	DEPRECIATION ($) STRAIGHT LINE	CAPITAL ($) RETURN ON UNRECOVERED	CAPITAL ($) RECOVERED PLUS RETURN
1	3189219.	1594609.	4145984.	7335203.
2	2870297.	1510683.	3731386.	6601683.
3	2583267.	1435148.	3358247.	5941514.
4	2324940.	1367612.	3022423.	5347363.
5	2092446.	1307779.	2720180.	4812627.
6	1883202.	1255468.	2448162.	4331364.
7	1694882.	1210630.	2203346.	3898228.
8	1525393.	1175380.	1983012.	3508405.
9	1372854.	1144045.	1784710.	3157565.
10	1235569.	1123244.	1606239.	2841808.
11	1112012.	1112012.	1445615.	2557627.
12	1000811.	1112012.	1301054.	2413066.
13	900730.	1112012.	1156492.	2268504.
14	810657.	1112012.	1011931.	2123943.
15	729591.	1112012.	867369.	1979381.
16	656632.	1112012.	722808.	1834820.
17	590969.	1112012.	578246.	1690258.
18	531872.	1112012.	433685.	1545697.
19	478685.	1112012.	289123.	1401135.
20	430816.	1112012.	144562.	1256573.

MODULE 2 (DOCK/TERM)

INITIAL INVESTMENT = $ 31892187.
SALVAGE VALUE = $ 0.
INTEREST (%) = 14.
LIFETIME (YEARS) = 20.
CAPITAL RECOVERY FACTOR = .15099
EQUIVALENT ANNUAL COST = $ 4815274.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	3189219.	1594609.	4464906.	7654125.
2	2870297.	1510683.	4018416.	6888712.
3	2583267.	1435148.	3616574.	6199841.
4	2324940.	1367612.	3254917.	5579857.
5	2092446.	1307779.	2929425.	5021871.
6	1883202.	1255408.	2636482.	4519684.
7	1694882.	1210650.	2372834.	4067716.
8	1525393.	1175360.	2135551.	3660944.
9	1372854.	1144045.	1921996.	3294850.
10	1235569.	1123244.	1729796.	2965365.
11	1112012.	1112012.	1556817.	2668828.
12	1000811.	1112012.	1401135.	2513147.
13	900730.	1112012.	1245453.	2357465.
14	810657.	1112012.	1089772.	2201783.
15	729591.	1112012.	934090.	2046102.
16	656632.	1112012.	778408.	1890420.
17	590969.	1112012.	622727.	1734739.
18	531872.	1112012.	467045.	1579057.
19	478685.	1112012.	311363.	1423375.
20	430816.	1112012.	155682.	1267694.

MODULE 2 (DOCK/TERM)

```
INITIAL INVESTMENT        = $    31892187.
SALVAGE VALUE             = $           0.
INTEREST (%)              =            15.
LIFETIME (YEARS)          =            20.
CAPITAL RECOVERY FACTOR   =        .15976
EQUIVALENT ANNUAL COST    = $     5095143.
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	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	3189219.	1594609.	4783828.	7973047.
2	2870297.	1510683.	4305445.	7175742.
3	2583267.	1435149.	3874901.	6458168.
4	2324940.	1367612.	3487411.	5812351.
5	2092446.	1307779.	3138670.	5231116.
6	1883202.	1255468.	2824803.	4708004.
7	1694882.	1210630.	2542322.	4237204.
8	1525393.	1173360.	2288090.	3813484.
9	1372854.	1144045.	2059281.	3432135.
10	1235569.	1123244.	1853353.	3088922.
11	1112012.	1112012.	1668018.	2780030.
12	1000811.	1112012.	1501216.	2613228.
13	900730.	1112012.	1334414.	2446426.
14	810657.	1112012.	1167612.	2279624.
15	729591.	1112012.	1000811.	2112823.
16	656632.	1112012.	834009.	1946021.
17	590969.	1112012.	667207.	1779219.
18	531872.	1112012.	500405.	1612417.
19	478685.	1112012.	333604.	1445615.
20	430816.	1112012.	166802.	1278814.

MODULE 2 (DOCK/TERM)

INITIAL INVESTMENT	= $	31892187.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	16.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.16867
EQUIVALENT ANNUAL COST	= $	5379160.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	3189219.	1594609.	5102750.	8291968.
2	2870297.	1516683.	4592475.	7462772.
3	2583267.	1435143.	4133227.	6716495.
4	2324940.	1347612.	3719905.	6044845.
5	2092446.	1307779.	3347914.	5440361.
6	1883202.	1255468.	3013123.	4896325.
7	1694882.	1210650.	2711811.	4406692.
8	1525393.	1173768.	2440630.	3966023.
9	1372854.	1144045.	2196567.	3569421.
10	1235569.	1123244.	1976910.	3212479.
11	1112012.	1112012.	1779219.	2891231.
12	1000811.	1112012.	1601297.	2713309.
13.	900730.	1112012.	1423375.	2535387.
14	810657.	1112012.	1245453.	2357465.
15	729591.	1112012.	1067531.	2179543.
16	656632.	1112012.	889610.	2001621.
17	590969.	1112012.	711688.	1823699.
18	531872.	1112012.	533766.	1645778.
19	478685.	1112012.	355844.	1467856.
20	430816.	1112012.	177922.	1289934.

DOUBLE 2 (DOCK/TERM)

INITIAL INVESTMENT = $ 31592187.
SALVAGE VALUE = $ 0.
INTEREST (%) = 17.
LIFETIME (YEARS) = 20.
CAPITAL RECOVERY FACTOR = .17769
EQUIVALENT ANNUAL COST = $ 5666934.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	3159219.	1594609.	5421672.	8610890.
2	2571297.	1510683.	4879505.	7749801.
3	2563267.	1435148.	4391554.	6974821.
4	2324940.	1367612.	3952399.	6277339.
5	2092446.	1307779.	3557159.	5649605.
6	1883202.	1255466.	3201443.	5084645.
7	1694882.	1210630.	2881299.	4576180.
8	1525393.	1173066.	2593169.	4118562.
9	1372854.	1144045.	2333852.	3706706.
10	1235569.	1123244.	2100467.	3336036.
11	1112012.	1112012.	1890420.	3002432.
12	1000811.	1112012.	1701378.	2813390.
13	900730.	1112012.	1512336.	2624348.
14	810657.	1112012.	1323294.	2435306.
15	729591.	1112012.	1134252.	2246264.
16	656632.	1112012.	945210.	2057222.
17	590969.	1112012.	756168.	1868180.
18	531872.	1112012.	567126.	1679138.
19	478685.	1112012.	378084.	1490096.
20	430816.	1112012.	189042.	1301054.

MODULE 3 (DOCK/TERM)

INITIAL INVESTMENT	= $	31892187.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	18.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.18682
EQUIVALENT ANNUAL COST	= $	5958098.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	3189219.	1594609.	5740594.	8929812.
2	2870297.	1510683.	5166534.	8036831.
3	2583267.	1435148.	4649881.	7233148.
4	2324940.	1367612.	4184893.	6509833.
5	2092446.	1307779.	3766404.	5858850.
6	1883202.	1255468.	3389763.	5272965.
7	1694882.	1210630.	3050787.	4745669.
8	1525393.	1173380.	2745708.	4271102.
9	1372854.	1144045.	2471137.	3843992.
10	1235569.	1123244.	2224024.	3459592.
11	1112012.	1112012.	2001621.	3113633.
12	1000811.	1112012.	1801459.	2913471.
13	900730.	1112012.	1601297.	2713309.
14	810657.	1112012.	1401135.	2513147.
15	729591.	1112012.	1200973.	2312985.
16	656632.	1112012.	1000811.	2112823.
17	590969.	1112012.	800649.	1912660.
18	531872.	1112012.	600486.	1712498.
19	478685.	1112012.	400324.	1512336.
20	430816.	1112012.	200162.	1312174.

MODULE 2 (DOCK/TERM)

INITIAL INVESTMENT	= $	31092187.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	19.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.19605
EQUIVALENT ANNUAL COST	= $	6252513.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	3189219.	1554609.	6059515.	9248734.
2	2870297.	1510683.	5453564.	8323861.
3	2583267.	1435148.	4908208.	7491475.
4	2324940.	1367612.	4417387.	6742327.
5	2092446.	1307779.	3975648.	6068095.
6	1883202.	1255465.	3578083.	5461285.
7	1694882.	1210630.	3220275.	4915157.
8	1525393.	1173380.	2898248.	4423641.
9	1372854.	1144045.	2608423.	3981277.
10	1235569.	1123244.	2347581.	3583149.
11	1112012.	1112012.	2112823.	3224834.
12	1000811.	1112012.	1901540.	3013552.
13	900730.	1112012.	1690256.	2802270.
14	810657.	1112012.	1478976.	2590988.
15	729591.	1112012.	1267694.	2379705.
16	656632.	1112012.	1056411.	2168423.
17	590969.	1112012.	845129.	1957141.
18	531872.	1112012.	633847.	1745859.
19	478685.	1112012.	422565.	1534576.
20	430816.	1112012.	211282.	1323294.

MODULE 2 (DOCK/TERM)

INITIAL INVESTMENT = $ 31892187.
SALVAGE VALUE = $ 0.
INTEREST (%) = 20.
LIFETIME (YEARS) = 20.
CAPITAL RECOVERY FACTOR = .20536
EQUIVALENT ANNUAL COST = $ 6549269.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	3189219.	1594609.	6378437.	9567656.
2	2870297.	1510663.	5740594.	8610890.
3	2583267.	1435148.	5166534.	7749801.
4	2324940.	1367612.	4649881.	6974821.
5	2092446.	1307779.	4184893.	6277339.
6	1883202.	1255406.	3766404.	5649605.
7	1694882.	1210650.	3389763.	5084645.
8	1525393.	1173380.	3050787.	4576180.
9	1372854.	1144045.	2745708.	4118562.
10	1235569.	1122244.	2471137.	3706706.
11	1112012.	1112012.	2224024.	3336036.
12	1000811.	1112012.	2001621.	3113633.
13	900730.	1112012.	1779219.	2891231.
14	810657.	1112012.	1556817.	2668828.
15	729591.	1112012.	1334414.	2446426.
16	656632.	1112012.	1112012.	2224024.
17	590969.	1112012.	889610.	2001621.
18	531872.	1112012.	667207.	1779219.
19	478685.	1112012.	444805.	1556817.
20	430816.	1112012.	222402.	1334414.

MODULE 2 (LOCK/TERM)

INITIAL INVESTMENT	= $	31892137.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	21.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.21474
EQUIVALENT ANNUAL COST	= $	6848680.

YEAR	DEPRECIATION ($) DOUBLE DECLINING BALANCE	STRAIGHT LINE	CAPITAL ($) RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	3189219.	1594609.	6697359.	9886578.
2	2870297.	1510683.	6027623.	8897920.
3	2583267.	1435148.	5424861.	8008128.
4	2324940.	1367612.	4882375.	7207315.
5	2092446.	1307779.	4394137.	6486584.
6	1883202.	1255465.	3954724.	5837926.
7	1694882.	1210651.	3559251.	5254133.
8	1525393.	1173360.	3203326.	4728720.
9	1372854.	1144045.	2882994.	4255848.
10	1235569.	1123244.	2594694.	3830263.
11	1112012.	1112012.	2335225.	3447237.
12	1000811.	1112012.	2101702.	3213714.
13	900730.	1112012.	1868180.	2980192.
14	810657.	1112012.	1634657.	2746669.
15	729591.	1112012.	1401135.	2513147.
16	656632.	1112012.	1167612.	2279624.
17	590969.	1112012.	934090.	2046102.
18	531872.	1112012.	700567.	1812579.
19	478685.	1112012.	467045.	1579057.
20	430816.	1112012.	233523.	1345534.

MODULE 2 (DOCK/TERM)

INITIAL INVESTMENT	= $	31892187.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	22.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.22420
EQUIVALENT ANNUAL COST	= $	7150265.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	3189219.	1594609.	7016281.	10205500.
2	2870297.	1510663.	6314653.	9184950.
3	2583267.	1435148.	5683188.	8266455.
4	2324940.	1367612.	5114869.	7439809.
5	2092446.	1307779.	4603382.	6695829.
6	1883202.	1255468.	4143044.	6026246.
7	1694882.	1210636.	3728740.	5423621.
8	1525393.	1173360.	3355866.	4881259.
9	1372854.	1144945.	3020279.	4393133.
10	1235569.	1123244.	2718251.	3953820.
11	1112012.	1112012.	2446426.	3558438.
12	1000811.	1112012.	2201783.	3313795.
13	900730.	1112012.	1957141.	3069153.
14	810657.	1112012.	1712498.	2824510.
15	729591.	1112012.	1467856.	2579868.
16	656632.	1112012.	1223213.	2335225.
17	590969.	1112012.	978570.	2090582.
18	531872.	1112012.	733928.	1845940.
19	478685.	1112012.	489285.	1601297.
20	430816.	1112012.	244643.	1356654.

MODULE 2 (DOCK/TERM)

INITIAL INVESTMENT = $ 31892187.
SALVAGE VALUE = $ 0.
INTEREST (%) = 23.
LIFETIME (YEARS) = 20.
CAPITAL RECOVERY FACTOR = .23372
EQUIVALENT ANNUAL COST = $ 7453858.

YEAR	DEPRECIATION ($) DOUBLE DECLINING BALANCE	DEPRECIATION ($) STRAIGHT LINE	CAPITAL ($) RETURN ON UNRECOVERED	CAPITAL ($) RECOVERED PLUS RETURN
1	3189219.	1594609.	7335203.	10524422.
2	2870297.	1514683.	6601683.	9471979.
3	2583267.	1435149.	5941514.	8524781.
4	2324940.	1367612.	5347363.	7672303.
5	2092446.	1307779.	4812627.	6905073.
6	1883202.	1255466.	4331364.	6214566.
7	1694882.	1210630.	3898228.	5593109.
8	1525393.	1175380.	3508405.	5033798.
9	1372854.	1144045.	3157565.	4530419.
10	1235569.	1123244.	2841808.	4077377.
11	1112012.	1112012.	2557627.	3669639.
12	1000811.	1112012.	2301865.	3413876.
13	900730.	1112012.	2046102.	3158114.
14	810657.	1112012.	1790339.	2902351.
15	729591.	1112012.	1534576.	2646588.
16	656632.	1112012.	1278814.	2390826.
17	590969.	1112012.	1023051.	2135063.
18	531872.	1112012.	767288.	1879300.
19	478685.	1112012.	511525.	1623537.
20	430816.	1112012.	255763.	1367775.

MODULE 2 (BOOK/TERM)

INITIAL INVESTMENT	= $	31892137.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	24.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.24329
EQUIVALENT ANNUAL COST	= $	7759171.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	3189219.	1594609.	7654125.	10843343.
2	2870297.	1510683.	6868712.	9759009.
3	2583267.	1435143.	6199841.	8783108.
4	2324940.	1367612.	5579857.	7904797.
5	2092446.	1307779.	5021871.	7114318.
6	1883202.	1255468.	4519684.	6402886.
7	1694882.	1210630.	4067716.	5762597.
8	1525393.	1173380.	3660944.	5186338.
9	1372854.	1144045.	3294850.	4667704.
10	1235569.	1122244.	2965365.	4200934.
11	1112012.	1112012.	2668828.	3780840.
12	1000811.	1112012.	2401946.	3513958.
13	900730.	1112012.	2135063.	3247075.
14	810657.	1112012.	1868180.	2980192.
15	729591.	1112012.	1601297.	2713309.
16	656632.	1112012.	1334414.	2446426.
17	590969.	1112012.	1067531.	2179543.
18	531872.	1112012.	800649.	1912660.
19	478685.	1112012.	533766.	1645778.
20	430816.	1112012.	266883.	1378895.

MODULE 2 (JACK/TERM)

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INITIAL INVESTMENT        = $   31892187.
SALVAGE VALUE             = $          0.
INTEREST (%)              =           25.
LIFETIME (YEARS)          =           20.
CAPITAL RECOVERY FACTOR   =       .25292
EQUIVALENT ANNUAL COST    = $    8066042.
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	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	3189219.	1594609.	7973047.	11162265.
2	2870297.	1510683.	7175742.	10046039.
3	2583267.	1435148.	6458168.	9041435.
4	2324940.	1367612.	5812351.	8137292.
5	2092446.	1307779.	5231116.	7323563.
6	1883202.	1255468.	4708005.	6591206.
7	1694882.	1210630.	4237204.	5932086.
8	1525393.	1173380.	3813484.	5338877.
9	1372854.	1144045.	3432135.	4804990.
10	1235569.	1123244.	3088922.	4324491.
11	1112012.	1112012.	2780030.	3892042.
12	1000811.	1112012.	2502027.	3614039.
13	900730.	1112012.	2224024.	3336036.
14	810657.	1112012.	1946021.	3058033.
15	729591.	1112012.	1668018.	2780030.
16	656632.	1112012.	1390015.	2502027.
17	590969.	1112012.	1112012.	2224024.
18	531872.	1112012.	834009.	1946021.
19	478685.	1112012.	556006.	1668018.
20	430816.	1112012.	278003.	1390015.

MODULE 3 (TRANSFER)

INITIAL INVESTMENT = $ 5911087.
SALVAGE VALUE = $ 0.
INTEREST (%) = 5.
LIFETIME (YEARS) = 20.
CAPITAL RECOVERY FACTOR = .08024
EQUIVALENT ANNUAL COST = $ 474321.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	591109.	295554.	295554.	886663.
2	531996.	279999.	265999.	797997.
3	473798.	265999.	239399.	718197.
4	430918.	253481.	215459.	646377.
5	387826.	242392.	193913.	581740.
6	349044.	232696.	174522.	523566.
7	314139.	224365.	157070.	471209.
8	282725.	217481.	141363.	424088.
9	254453.	212044.	127226.	381679.
10	229008.	206189.	114504.	343511.
11	206107.	206107.	103053.	309160.
12	185496.	206107.	92748.	298855.
13	166947.	206107.	82443.	288550.
14	150252.	206107.	72137.	278244.
15	135227.	206107.	61832.	267939.
16	121704.	206107.	51527.	257634.
17	109534.	206107.	41221.	247328.
18	98580.	206107.	30916.	237023.
19	88722.	206107.	20611.	226718.
20	79850.	206107.	10305.	216412.

MODULE 3 (TRANSFER)

INITIAL INVESTMENT	= $	5911067.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	6.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.08718
EQUIVALENT ANNUAL COST	= $	515356.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	591109.	295554.	354665.	945774.
2	531996.	279999.	319199.	651197.
3	478796.	265999.	287279.	766077.
4	430918.	253481.	258551.	689469.
5	387826.	242392.	232696.	620522.
6	349044.	232696.	209426.	558470.
7	314139.	224365.	188484.	502623.
8	282725.	217481.	169635.	452361.
9	254453.	212044.	152672.	407125.
10	229008.	208189.	137405.	366412.
11	206107.	206107.	123664.	329771.
12	185496.	206107.	111298.	317405.
13	166947.	206107.	98931.	305038.
14	150252.	206107.	86565.	292672.
15	135227.	206107.	74198.	280305.
16	121704.	206107.	61832.	267939.
17	109534.	206107.	49466.	255573.
18	98580.	206107.	37099.	243206.
19	88722.	206107.	24733.	230840.
20	79850.	206107.	12366.	218473.

MODULE 3 (TRANSFER)

INITIAL INVESTMENT	= $	5911087.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	7.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.09439
EQUIVALENT ANNUAL COST	= $	557965.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	591109.	295554.	413776.	1004885.
2	531998.	279999.	372398.	904396.
3	478798.	265999.	335159.	813957.
4	430918.	253481.	301643.	732561.
5	387826.	242392.	271478.	659305.
6	349044.	232696.	244331.	593374.
7	314139.	224365.	219898.	534037.
8	282725.	217481.	197908.	480633.
9	254453.	212044.	178117.	432570.
10	229008.	208189.	160305.	389313.
11	206107.	206107.	144275.	350382.
12	185496.	206107.	129847.	335954.
13	166947.	206107.	115420.	321527.
14	150252.	206107.	100992.	307099.
15	135227.	206107.	86565.	292672.
16	121704.	206107.	72137.	278244.
17	109534.	206107.	57710	263817.
18	98580.	206107.	43282.	249389.
19	88722.	206107.	28855.	234962.
20	79850.	206107.	14427.	220534.

MODULE 3 (TRANSFER)

INITIAL INVESTMENT = $ 5911087.
SALVAGE VALUE = $ 0.
INTEREST (%) = 8.
LIFETIME (YEARS) = 20.
CAPITAL RECOVERY FACTOR = .10185
EQUIVALENT ANNUAL COST = $ 602057.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	591109.	295554.	472887.	1063996.
2	531998.	279999.	425598.	957596.
3	478798.	265999.	383038.	861836.
4	430918.	253461.	344735.	775653.
5	387826.	242392.	310261.	698088.
6	349044.	232696.	279235.	628279.
7	314139.	224365.	251312.	565451.
8	282725.	217461.	226180.	508906.
9	254453.	212044.	203562.	458015.
10	229008.	208189.	183206.	412214.
11	206107.	206107.	164885.	370992.
12	185496.	206107.	148397.	354504.
13	166947.	206107.	131908.	338015.
14	150252.	206107.	115420.	321527.
15	135227.	206107.	98931.	305038.
16	121704.	206107.	82443.	288550.
17	109534.	206107.	65954.	272061.
18	98580.	206107.	49466.	255573.
19	88722.	206107.	32977.	239084.
20	79850.	206107.	16489.	222595.

MODULE 3 (TRANSFER)

INITIAL INVESTMENT	= $	5911087.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	9.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.10955
EQUIVALENT ANNUAL COST	= $	647539.

YEAR	DEPRECIATION ($) DOUBLE DECLINING BALANCE	DEPRECIATION ($) STRAIGHT LINE	CAPITAL ($) RETURN ON UNRECOVERED	CAPITAL ($) RECOVERED PLUS RETURN
1	591109.	295554.	531998.	1123107.
2	531998.	279999.	478798.	1010796.
3	478798.	265999.	430918.	909716.
4	430918.	253481.	387826.	818745.
5	387826.	242392.	349044.	736870.
6	349044.	232696.	314139.	663183.
7	314139.	224365.	282725.	596865.
8	282725.	217481.	254453.	537178.
9	254453.	212044.	229008.	483461.
10	229008.	208169.	206107.	435114.
11	206107.	206107.	185496.	391603.
12	185496.	206107.	166947.	373053.
13	166947.	206107.	148397.	354504.
14	150252.	206107.	129847.	335954.
15	135227.	206107.	111298.	317405.
16	121704.	206107.	92748.	298855.
17	109534.	206107.	74198.	280305.
18	98580.	206107.	55649.	261756.
19	88722.	206107.	37099.	243206.
20	79850.	206107.	18550.	224656.

MODULE 3 (TRANSFER)

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INITIAL INVESTMENT          = $     5911057.
SALVAGE VALUE               = $           0.
INTEREST (%)                =            10.
LIFETIME (YEARS)            =            20.
CAPITAL RECOVERY FACTOR     =        .11746
EQUIVALENT ANNUAL COST      = $      694314.
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	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	591109.	295554.	591109.	1182217.
2	531998.	279999.	531998.	1063996.
3	478798.	265999.	478798.	957596.
4	430918.	253481.	430918.	861836.
5	387826.	242392.	387826.	775653.
6	349044.	232696.	349044.	698088.
7	314139.	224365.	314139.	628279.
8	282725.	217481.	282725.	565451.
9	254453.	212044.	254453.	508906.
10	229008.	208189.	229008.	458015.
11	206107.	206107.	206107.	412214.
12	185496.	206107.	185496.	391603.
13	166947.	206107.	164885.	370992.
14	150252.	206107.	144275.	350382.
15	135227.	206107.	123664.	329771.
16	121704.	206107.	103053.	309160.
17	109534.	206107.	82443.	288550.
18	98580.	206107.	61832.	267939.
19	88722.	206107.	41221.	247328.
20	79850.	206107.	20611.	226718.

MODULE 3 (TRANSFER)

INITIAL INVESTMENT	= $	5911067.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	11.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.12558
EQUIVALENT ANNUAL COST	= $	742288.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	591109.	295554.	650220.	1241328.
2	531998.	279999.	585198.	1117195.
3	478798.	265999.	526678.	1005476.
4	430918.	253461.	474010.	904928.
5	387826.	242392.	426609.	814435.
6	349044.	232696.	383948.	732992.
7	314139.	224305.	345553.	659693.
8	282725.	217461.	310998.	593723.
9	254453.	212044.	279898.	534351.
10	229008.	208159.	251908.	480916.
11	206107.	206107.	226718.	432824.
12	185496.	206107.	204046.	410153.
13	166947.	206107.	181374.	387481.
14	150252.	206107.	158702.	364809.
15	135227.	206107.	136031.	342137.
16	121704.	206107.	113359.	319466.
17	109534.	206107.	90687.	296794.
18	98580.	206107.	68015.	274122.
19	88722.	206107.	45344.	251450.
20	79850.	206107.	22672.	228779.

MODULE 3 (TRANSFER)

INITIAL INVESTMENT	= $	5911087.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	12.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.13388
EQUIVALENT ANNUAL COST	= $	791369.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	591109.	295554.	709330.	1300439.
2	531998.	279999.	638397.	1170395.
3	478798.	265999.	574558.	1053356.
4	430918.	253461.	517102.	948020.
5	387826.	242392.	465392.	853218.
6	349044.	232696.	418853.	767896.
7	314139.	224365.	376967.	691107.
8	282725.	217461.	339271.	621996.
9	254453.	212044.	305344.	559796.
10	229008.	208169.	274809.	503817.
11	206107.	206107.	247328.	453435.
12	185496.	206107.	222595.	428702.
13	166947.	206107.	197863.	403969.
14	150252.	206107.	173130.	379237.
15	135227.	206107.	148397.	354504.
16	121704.	206107.	123664.	329771.
17	109534.	206107.	98931.	305038.
18	98580.	206107.	74198.	280305.
19	88722.	206107.	49466.	255573.
20	79850.	206107.	24733.	230840.

MODULE 3 (TRANSFER)

INITIAL INVESTMENT	= $	5911057.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	15.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.14235
EQUIVALENT ANNUAL COST	= $	841466.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	591109.	295554.	768441.	1359550.
2	531996.	279999.	691597.	1223595.
3	478796.	265999.	622437.	1101235.
4	430918.	253461.	560194.	991112.
5	387826.	242392.	504174.	892001.
6	349044.	232696.	453757.	802801.
7	314139.	224365.	408381.	722521.
8	282725.	217481.	367543.	650269.
9	254453.	212044.	330789.	585242.
10	229008.	208189.	297710.	526718.
11	206107.	206107.	267939.	474046.
12	185496.	206107.	241145.	447252.
13	166947.	206107.	214351.	420458.
14	150252.	206107.	187557.	393664.
15	135227.	206107.	160763.	366870.
16	121704.	206107.	133969.	340076.
17	109534.	206107.	107176.	313282.
18	98580.	206107.	80382.	286489.
19	88722.	206107.	53588.	259695.
20	79850.	206107.	26794.	232901.

MODULE 3 (TRANSFER)

```
INITIAL INVESTMENT         = $     5911087.
SALVAGE VALUE              = $          0.
INTEREST (%)               =           14.
LIFETIME (YEARS)           =           20.
CAPITAL RECOVERY FACTOR    =       .15099
EQUIVALENT ANNUAL COST     = $     892491.
```

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	591109.	295554.	827552.	1418661.
2	531998.	279999.	744797.	1276795.
3	478798.	265999.	670317.	1149115.
4	430918.	253461.	603286.	1034204.
5	387826.	242392.	542957.	930783.
6	349044.	232696.	488661.	837705.
7	314139.	224365.	439795.	753935.
8	282725.	217461.	395816.	678541.
9	254453.	212044.	356234.	610687.
10	229008.	208169.	320611.	549618.
11	206107.	206107.	288550.	494656.
12	185496.	206107.	259695.	465802.
13	166947.	206107.	230840.	436947.
14	150252.	206107.	201985.	408092.
15	135227.	206107.	173130.	379237.
16	121704.	206107.	144275.	350382.
17	109534.	206107.	115420.	321527.
18	98580.	206107.	86565.	292672.
19	88722.	206107.	57710.	263817.
20	79850.	206107.	28855.	234962.

MODULE 3 (TRANSFER)

```
INITIAL INVESTMENT       = $     5911087.
SALVAGE VALUE            = $          0.
INTEREST (%)             =           15.
LIFETIME (YEARS)         =           20.
CAPITAL RECOVERY FACTOR  =       .15976
EQUIVALENT ANNUAL COST   = $     944364.
```

YEAR	DEPRECIATION ($) DOUBLE DECLINING BALANCE	STRAIGHT LINE	CAPITAL ($) RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	591109.	295554.	886663.	1477772.
2	531998.	279999.	797997.	1329995.
3	478798.	265999.	718197.	1196995.
4	430918.	253461.	646377.	1077296.
5	387826.	242392.	581740.	969566.
6	349044.	232696.	523566.	872609.
7	314139.	224365.	471209.	785349.
8	282725.	217461.	424088.	706814.
9	254453.	212044.	381679.	636132.
10	229008.	206189.	343511.	572519.
11	206107.	206107.	309160.	515267.
12	185496.	206107.	278244.	484351.
13	166947.	206107.	247328.	453435.
14	150252.	206107.	216412.	422519.
15	135227.	206107.	185496.	391603.
16	121704.	206107.	154580.	360687.
17	109534.	206107.	123664.	329771.
18	98580.	206107.	92748.	298855.
19	88722.	206107.	61832.	267939.
20	79850.	206107.	30916.	237023.

MODULE 3 (TRANSFER)

INITIAL INVESTMENT	= $	5911067.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	16.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.16867
EQUIVALENT ANNUAL COST	= $	997005.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	591109.	295554.	945774.	1536883.
2	531996.	279999.	851197.	1383194.
3	478796.	265997.	766077.	1244875.
4	430916.	253461.	689469.	1120387.
5	387826.	242392.	620522.	1008349.
6	349044.	232696.	558470.	907514.
7	314139.	224365.	502623.	816762.
8	282725.	217461.	452361.	735086.
9	254453.	212044.	407125.	661578.
10	229008.	206107.	366412.	595420.
11	206107.	206107.	329771.	535878.
12	165496.	206107.	296794.	502901.
13	166947.	206107.	263817.	469924.
14	150252.	206107.	230840.	436947.
15	135227.	206107.	197863.	403969.
16	121704.	206107.	164886.	370992.
17	109534.	206107.	131908.	338015.
18	98580.	206107.	98931.	305038.
19	88722.	206107.	65954.	272061.
20	79850.	206107.	32977.	239084.

MODULE 3 (TRANSFER)

INITIAL INVESTMENT	= $	5911087.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	17.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.17769
EQUIVALENT ANNUAL COST	= $	1050343.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	591109.	295554.	1004885.	1595993.
2	531998.	279999.	904396.	1436394.
3	478798.	265999.	813957.	1292755.
4	430918.	253481.	732561.	1163479.
5	387826.	242392.	659305.	1047131.
6	349044.	232696.	593374.	942418.
7	314139.	224365.	534037.	848176.
8	282725.	217461.	480633.	763359.
9	254453.	212044.	432570.	687023.
10	229008.	208189.	389313.	618321.
11	206107.	206107.	350382.	556489.
12	185496.	206107.	315344.	521450.
13	166947.	206107.	283805.	486412.
14	150252.	206107.	245267.	451374.
15	135227.	206107.	210229.	416336.
16	121704.	206107.	175191.	381298.
17	109534.	206107.	140153.	346260.
18	98580.	206107.	105115.	311221.
19	88722.	206107.	70076.	276183.
20	79850.	206107.	35038.	241145.

MODULE 3 (TRANSFER)

INITIAL INVESTMENT	= $	5911087.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	18.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.18682
EQUIVALENT ANNUAL COST	= $	1104309.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	591109.	295554.	1063996.	1655104.
2	531998.	279999.	957596.	1489594.
3	478798.	265999.	861836.	1340635.
4	430918.	253481.	775653.	1206571.
5	387826.	242392.	698088.	1085914.
6	349044.	232696.	628279.	977323.
7	314139.	224385.	565451.	879590.
8	282725.	217481.	508906.	791631.
9	254453.	212044.	458015.	712468.
10	229008.	208189.	412214.	641221.
11	206107.	206107.	370992.	577099.
12	185496.	206107.	333893.	540000.
13	166947.	206107.	296794.	502901.
14	150252.	206107.	259695.	465802.
15	135227.	206107.	222595.	428702.
16	121704.	206107.	185496.	391603.
17	109534.	206107.	148397.	354504.
18	98580.	206107.	111298.	317405.
19	88722.	206107.	74198.	280305.
20	79850.	206107.	37099.	243206.

MODULE 3 (TRANSFER)

INITIAL INVESTMENT	= $	5911087.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	19.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.19605
EQUIVALENT ANNUAL COST	= $	1158641.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	591109.	295554.	1123107.	1714215.
2	531998.	279999.	1010796.	1542794.
3	478798.	265999.	909716.	1388514.
4	430918.	253461.	818745.	1249663.
5	387826.	242792.	736870.	1124697.
6	349044.	232696.	663183.	1012227.
7	314139.	224365.	596865.	911004.
8	282725.	217481.	537178.	819904.
9	254453.	212044.	483461.	737913.
10	229008.	208169.	435115.	664122.
11	206107.	206107.	391603.	597710.
12	185496.	206107.	352443.	558550.
13	166947.	206107.	313282.	519389.
14	150252.	206107.	274122.	480229.
15	135227.	206107.	234962.	441069.
16	121704.	206107.	195802.	401908.
17	109534.	206107.	156641.	362748.
18	98580.	206107.	117481.	323588.
19	88722.	206107.	78321.	284427.
20	79850.	206107.	39160.	245267.

MODULE 3 (TRANSFER)

INITIAL INVESTMENT	= $	5911087.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	20.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.20536
EQUIVALENT ANNUAL COST	= $	1213660.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	591109.	295554.	1182217.	1773326.
2	531998.	279999.	1063996.	1595993.
3	478798.	265999.	957596.	1436394.
4	430918.	253461.	861836.	1292755.
5	387826.	242392.	775653.	1163479.
6	349044.	232696.	698088.	1047131.
7	314139.	224305.	628279.	942418.
8	282725.	217461.	565451.	848176.
9	254453.	212044.	508906.	763359.
10	229008.	206109.	458015.	687023.
11	206107.	206107.	412214.	618321.
12	185496.	206107.	370992.	577099.
13	166947.	206107.	329771.	535878.
14	150252.	206107.	288550.	494656.
15	135227.	206107.	247328.	453435.
16	121704.	206107.	206107.	412214.
17	109534.	206107.	164886.	370992.
18	98580.	206107.	123664.	329771.
19	88722.	206107.	82443.	288550.
20	79850.	206107.	41221.	247328.

MODULE 3 (TRANSFER)

INITIAL INVESTMENT	= $	5911087.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	21.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.21474
EQUIVALENT ANNUAL COST	= $	1269375.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	591109.	295554.	1241328.	1832437.
2	531998.	279999.	1117195.	1649193.
3	478798.	265999.	1005476.	1484274.
4	430918.	253481.	904928.	1335847.
5	387826.	242392.	814435.	1202262.
6	349044.	232696.	732992.	1082036.
7	314139.	224305.	659693.	973832.
8	282725.	217481.	593723.	876449.
9	254453.	212044.	534351.	788804.
10	229008.	208169.	460916.	709924.
11	206107.	206107.	432824.	638931.
12	185496.	206107.	389542.	595649.
13	166947.	206107.	346260.	552366.
14	150252.	206107.	302977.	509084.
15	135227.	206107.	259695.	465802.
16	121704.	206107.	216412.	422519.
17	109534.	206107.	173130.	379237.
18	98580.	206107.	129847.	335954.
19	88722.	206107.	86565.	292672.
20	79850.	206107.	43282.	249389.

MODULE 3 (TRANSFER)

INITIAL INVESTMENT	= $	5911087.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	22.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.22420
EQUIVALENT ANNUAL COST	= $	1325277.

YEAR	DEPRECIATION ($) DOUBLE DECLINING BALANCE	DEPRECIATION ($) STRAIGHT LINE	CAPITAL ($) RETURN ON UNRECOVERED	CAPITAL ($) RECOVERED PLUS RETURN
1	591109.	295554.	1300439.	1891548.
2	531998.	279999.	1170395.	1702393.
3	478798.	265999.	1053356.	1532154.
4	430918.	253481.	948020.	1378938.
5	387826.	242392.	853218.	1241045.
6	349044.	232696.	767896.	1116940.
7	314139.	224385.	691107.	1005246.
8	282725.	217481.	621996.	904721.
9	254453.	212044.	559796.	814249.
10	229008.	208189.	503817.	732824.
11	206107.	206107.	453435.	659542.
12	185496.	206107.	408092.	614198.
13	166947.	206107.	362748.	568855.
14	150252.	206107.	317405.	523511.
15	135227.	206107.	272061.	478168.
16	121704.	206107.	226718.	432824.
17	109534.	206107.	181374.	387481.
18	98580.	206107.	136031.	342137.
19	88722.	206107.	90687.	296794.
20	79850.	206107.	45344.	251450.

MODULE 3 (TRANSFER)

INITIAL INVESTMENT	= $	5911097.
SALVAGE VALUE	= $	0.
INTEREST (%)	=	23.
LIFETIME (YEARS)	=	20.
CAPITAL RECOVERY FACTOR	=	.23372
EQUIVALENT ANNUAL COST	= $	1381542.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	591109.	295554.	1359550.	1950659.
2	531998.	279999.	1223595.	1755593.
3	478798.	265999.	1101235.	1580034.
4	430918.	253401.	991112.	1422030.
5	387826.	242392.	892001.	1279827.
6	349044.	232696.	802801.	1151844.
7	314139.	224305.	722521.	1036660.
8	282725.	217461.	650269.	932994.
9	254453.	212044.	585242.	839695.
10	229007.	208169.	526718.	755725.
11	206107.	206107.	474046.	680153.
12	185496.	206107.	426641.	632748.
13	166947.	206107.	379237.	585344.
14	150252.	206107.	331832.	537939.
15	135227.	206107.	284427.	490534.
16	121704.	206107.	237023.	443130.
17	109534.	206107.	189618.	395725.
18	98580.	206107.	142214.	348321.
19	88722.	206107.	94809.	300916.
20	79850.	206107.	47405.	253511.

MODULE 3 (TRANSFER)

```
INITIAL INVESTMENT        = $    5911087.
SALVAGE VALUE             = $          0.
INTEREST (%)              =           24.
LIFETIME (YEARS)          =           20.
CAPITAL RECOVERY FACTOR   =       .24329
EQUIVALENT ANNUAL COST    = $    1435131.
```

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	591109.	295554.	1418661.	2009770.
2	531998.	279999.	1276795.	1808793.
3	478798.	265999.	1149115.	1627913.
4	430918.	253461.	1034204.	1465122.
5	387826.	242392.	930783.	1318610.
6	349044.	232696.	837705.	1186749.
7	314139.	224385.	753935.	1068074.
8	282725.	217481.	678541.	961267.
9	254453.	212044.	610687.	865140.
10	229008.	206169.	549618.	778626.
11	206107.	206107.	494656.	700763.
12	185496.	206107.	445191.	651298.
13	166947.	206107.	395725.	601832.
14	150252.	206107.	346260.	552366.
15	135227.	206107.	296794.	502901.
16	121704.	206107.	247328.	453435.
17	109534.	206107.	197863.	403969.
18	98580.	206107.	143397.	354504.
19	88722.	206107.	98931.	305038.
20	79850.	206107.	49466.	255573.

MODULE 3 (TRANSFER)

INITIAL INVESTMENT = $ 5911088.
SALVAGE VALUE = $ 0.
INTEREST (%) = 25.
LIFETIME (YEARS) = 20.
CAPITAL RECOVERY FACTOR = .25292
EQUIVALENT ANNUAL COST = $ 1495008.

	DEPRECIATION ($)		CAPITAL ($)	
YEAR	DOUBLE DECLINING BALANCE	STRAIGHT LINE	RETURN ON UNRECOVERED	RECOVERED PLUS RETURN
1	591109.	295554.	1477772.	2068880.
2	531998.	279999.	1329995.	1861992.
3	478798.	265999.	1196995.	1675793.
4	430918.	253481.	1077296.	1508214.
5	387826.	242392.	969566.	1357392.
6	349044.	232696.	872609.	1221653.
7	314139.	224385.	785349.	1099488.
8	282725.	217481.	706814.	989539.
9	254453.	212044.	636132.	890585.
10	229008.	208189.	572519.	801527.
11	206107.	206107.	515267.	721374.
12	185496.	206107.	463740.	669847.
13	166947.	206107.	412214.	618321.
14	150252.	206107.	360687.	566794.
15	135227.	206107.	309160.	515267.
16	121704.	206107.	257634.	463740.
17	109534.	206107.	206107.	412214.
18	98580.	206107.	154580.	360687.
19	88722.	206107.	103053.	309160.
20	79850.	206107.	51527.	257634.

APPENDIX B

Computer Code

COMPUTER CODE DATA INPUT DESCRIPTION

The computer code contained in Appendix B contains sufficient capability to provide a range of output values from which economic decisions may evolve. The inputs required are contained on one card per module. The data is arranged on each card as follows:

Col. 1 - 10	initial investment value
Col. 14 - 15	lifetime value
Col. 18 - 37	module identification

The computer code as presently structured will provide output values associated with interest rates of 8 to 25% in integer increments. Furthermore, any choice of initial investment values less than 10^{10} may be utilized. Integer values of lifetime less than 100 are acceptable. Salvage value is currently established at zero, with considerable computer code modification required for acceptance of other salvage values. The number of modules which may be considered is not limited. All input data must be right justified in their respective data fields.

COMPUTER CODE PORTABILITY

The economic trade-off analysis program has been implemented in a higher level language called FORTRAN which is available on a majority of today's modern digital computers. The language features used comply with the American National Standards Institute (ANSI) FORTRAN Standard X3.9 - 1966 and X3.9 - 1977. This approach was used to ensure portability of the code between different manufacturers' computers and FORTRAN compilers. For example, the program will run unchanged, except for the job control cards on the CDC 6600.

```
      SUBROUTINE DEPREC (DEP,ENVEST,N,J,TYPE,DDB,STRLN,X,RETURC)
      IF (J.GT.1) GO TO 62
      BOOK = ENVEST
      SBOOK = ENVEST
   62 IF (TYPE.EQ.3) GO TO 63
      STRLN =SBOOK/(FLOAT(N)-FLOAT(J)+1)
C *** DOUBLE DECLINING BALANCE ***
   63 D = 2/FLOAT(N)
      DDB = D*BOOK
      RETURC =SBOOK*X
      IF (TYPE.EQ.3) GO TO 65
      IF (STRLN.GT.DDB) GO TO 65
      DEP = DDB
      BOOK = BOOK-DDB
      SBOOK = BOOK
      RETURN
   65 DEP = STRLN
      SBOOK = SBOOK - DEP
      BOOK = BOOK-DDB
      TYPE = 3
      RETURN
      END
```

```
            DIMENSION IA(5)
            INTEGER TYPE
     10     READ (5,12,END=80) INVEST,N,(IA(I),I=1,5)
            ENVEST = INVEST
            DO 60 I=5,25
            TYPE = 2
            X = FLOAT(I)/100
            AP = (X*(1+X)** N)/((1+X)** N-1)
            ANCOST =    ENVEST*AP
            WRITE(6,18) (IA(K),K=1,5),INVEST,I,N,AP,ANCOST
            WRITE (6,14)
            DO 50 J = 1,N
            IF(TYPE .GT. 0)CALL DEPREC(DEP,ENVEST,N,J,TYPE,DDB,STRLN,X,RETURC)
            CAPRR = RETURC + DEP
            WRITE(6,15) J,DDB,STRLN,RETURC,CAPRR
     50     CONTINUE
     60     CONTINUE
            GO TO 10
     80     STOP
     C
     12     FORMAT(I10,2X,I3,2X,5A4)
     14     FORMAT(10X,T24,'DEPRECIATION ($)',T55,'CAPITAL ($)',
          A  //,10X,T22,'DOUBLE',T52,'RETURN',T66,'RECOVERED',
          B /,10X,T21,'DECLINING',T35,'STRAIGHT',T54,'ON',T68,'PLUS',
          C  /,10X,T11,'YEAR',T22,'BALANCE',T37,'LINE',T50,'UNRECOVERED',
          D  T67,'RETURN',/)
     15     FORMAT(10X,I3,T20, 4(F10.0,5X),/)
     18     FORMAT(1H1,T40,5A4,//,10X,'INITIAL INVESTMENT',T35,'= $ ',I10,'.',
          A /,10X,                'SALVAGE VALUE',T35,'= $ ',T48,'0.',
          B /,10X,       'INTEREST (%)',T35,'=',T47,I2,'.',
          C /,10X,       'LIFETIME (YEARS)',T35,'=',T47,I2,'.',
          D /,10X,       'CAPITAL RECOVERY FACTOR',T35,'= ',F13.5,
          E /,10X,       'EQUIVALENT ANNUAL COST',T35,'= $ ',F11.0,///)
            END
```

END

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